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MANUAL OF METHODS FOR FISHERIES RESOURCE SURVEY AND APPRAISAL

PART 2. THE USE OF ACOUSTIC INSTRUMENTS FOR FISH DETECTION AND ABUNDANCE ESTIMATION

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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PART 2. THE USE OF ACOUSTIC INSTRUMENTS FOR FISH DETECTION AND ABUNDANCE ESTIMATION

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NOTE

A preliminary version of the present manual was issued in 1969 as FAO Fisheries Technical Paper No. 83, *Manual of methods for fish stock assessment.* Part 5. *The use of acoustic instruments in fish detection and fish abundance estimation.* This Technical Paper was based on the *Report of the fourth session of the Advisory Committee on Marine Resources Research, 16-21 January 1967. Report of ACMRR Working Party on Direct and Speedier Estimation of Fish Abundance.* FAO Fisheries Reports No. 41, Suppl. 1. B.B. Parrish was the convener.

The preliminary manual was used as the basis for lectures at:

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The present manual is based on the experience gained at these training centres and many parts have been updated to include the most recent developments and techniques. The large and international list of contributors gives a fair indication of the extent of this revision.

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INTRODUCTION

Acoustic methods for fish finding and for commercial fishing operations have been a regular feature of most developed fishing fleets for over 20 years. During this time many advances and improvements have been made to enable the fisherman to use echo sounders and sonars to increase his catches and improve his chances of success. The use of these instruments for research by scientists, however, has only recently become commonplace.

Fishery scientists need population estimates made independently of fishery statistics of catch and effort and tagging experiments, and methods are also required for the rapid exploration of unexploited stocks. An increasing emphasis has been placed in recent years on the problems of direct and speedier estimation of fish populations, and methods of sizing and counting fish with echo sounders and sonars are now developing rapidly. As no manual or textbook at present exists which specifically deals with this subject, the present publication attempts to present a summary of the state of knowledge in the use of acoustics for fisheries resource survey and appraisal.

The manual aims at giving the fisheries scientist a thorough understanding of the basic theory involved in his use of underwater acoustics and in the more precise application of echo sounders and sonars for abundance estimation. It is not intended to be a handbook on fish counting.

At any given time the amount of fish T (in weight or number) within an area A can be written:

$$T = \int_A \rho_{1A}\, dA + \int_A \rho_{2A}\, dA + \ldots\ldots + \int_A \rho_{nA}\, dA$$

where ρ_A is the density of fish (weight or number per unit area) and 1, 2....n refer to the different species within the area. In order to obtain estimates of T, by integration of the right-hand side of the above expression, one must be able to:

(*a*) discriminate between species;

(*b*) make synoptic distribution charts of ρ_A for each species throughout the area.

This manual does not give complete solutions to the problems involved in (*a*) and (*b*) but rather an outline of the present state of the methods developed to solve them. These techniques are improving rapidly, and the last section gives some idea of the possibilities which might be within reach in the very near future.

SECTION 1. PHYSICAL PROPERTIES OF SOUND IN WATER: ITS PROPAGATION AND REFLECTION FROM TARGETS

1.1 Propagation of sound

1.1.1 Formation of sound waves

Sound may be defined as the transfer of energy through a compressible medium by means of small vibrations of individual particles of the medium. In fluids such as air and water, the only significant mode of vibration is longitudinal, where the particles of the medium move to and fro in the same direction as the propagation of energy. The simplest type of sound is produced by a vibrating surface which moves backward and forward in a regular harmonic motion.

During the vibration of such a surface in water, the water particles in contact with the surface are displaced by it. When the surface is at rest the pressure exerted on the water particles in contact with it is the hydrostatic pressure, corresponding to the height of the water column lying above it, but when it begins to move it exerts an excess pressure on them, its magnitude being directly proportional to the velocity of movement of the surface, that is

$$p = Zu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where p = excess pressure, u = velocity of movement, Z = constant, referred to later. Thus, the pressure will be zero at the points of maximum amplitude of displacement of the water particles, when their velocity is zero, and greatest at the point where they pass the "at rest" position, when their velocity is greatest. These variations in amplitude of displacement and excess pressure with time, of water particles in contact with a harmonically vibrating surface, are shown diagrammatically in Figure 1.1.

This shows that a new cycle of vibration commences when the vibrating surface returns to its original starting position, having passed the points of maximum displacement on either side of it. The number of such cycles completed in unit time is called the *frequency* of the sound source, and is measured in Hertz (Hz). This was formerly expressed in cycles per second (c/s). One thousand Hertz are expressed as 1 kHz (formerly 1 Kc/s).

The above conditions apply to the situation at the face of the vibrating surface. It is necessary to consider next the effect of the vibrating surface on the water particles at increasing distance from it.

If spreading and absorption of the sound are ignored, it can be shown that the pressure and particle velocity at a point distant L from the vibrating surface are the same as at the surface with a time lag

$$t = \frac{L}{c}$$

as illustrated in Figure 1.2.

Clearly, c is the velocity with which the disturbance passes through the water, and is called the *sound velocity*.

It is evident, therefore, that the vibrating sound source produces pressure variations in the water column which change periodically with both time and distance from the source, forming *sound waves*, as shown in Figure 1.3. The length of one wave, termed the *wavelength*, λ, is related to the frequency, f, of the sound source and the sound velocity, c, by the well-known relationship:

$$\lambda = \frac{c}{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Provided that the excess pressure p is small compared with the hydrostatic pressure, c depends only on the density and compressibility of the water according to the formula

$$c = \sqrt{\frac{1}{\rho K}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

or

$$c = \sqrt{\frac{E}{\rho}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where ρ is the density, K the compressibility and $E = \frac{1}{K}$ the bulk modulus of elasticity of the water. For sea water, both the density and elasticity are functions of temperature, salinity and depth, and the velocity of sound can be expressed in terms of these variables as

$$c = 1400 + 4.9\ t - 0{\cdot}044\ t^2 + \left(1.32 - \frac{t}{100}\right) S + 0.018 \left(1 - \frac{t}{100}\right)\ d$$

$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$

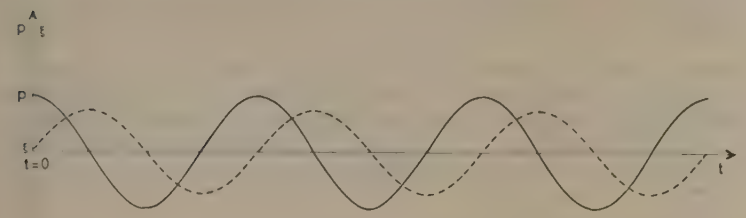


FIGURE 1.1 - Particle displacement, ξ, and pressure, p, as function of time, t, at the sound source, resulting from a harmonic vibrating material surface.

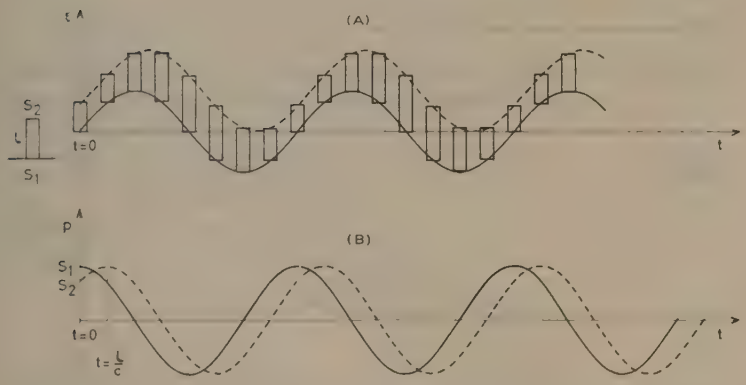


FIGURE 1.2 - The variation with time of displacement (A) and pressure (B) at the two end sides, S_1 and S_2, of a water column of length L.

where t is the temperature (C°), S salinity (per mille), d depth (metres) and c is in metres per second.

Values of velocity derived from this equation are shown graphically in Figure 1.4.

In sonar, sound is usually transmitted as pulses of a certain duration sent at regular intervals. The duration of each pulse is called the *pulse length* τ (milliseconds) which therefore covers $c\ \tau$ millimetres of water, when c is m/sec and τ milliseconds.

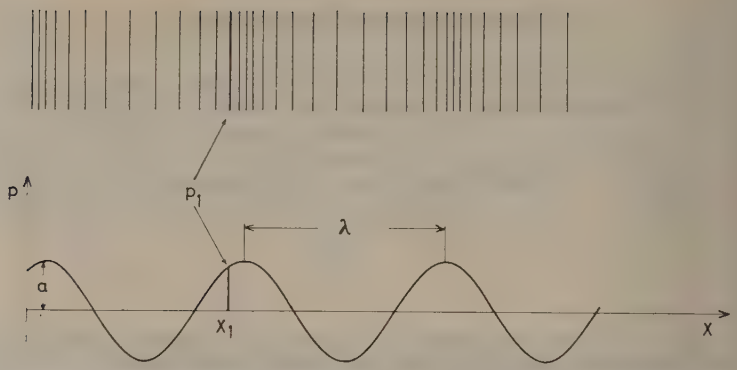


FIGURE 1.3 - The distribution of pressure at a certain time along the normal to a plane sound source of infinite size. (Amplitude, a, wavelength, λ, and wave front, p_1, at a distance x_1 are indicated.)

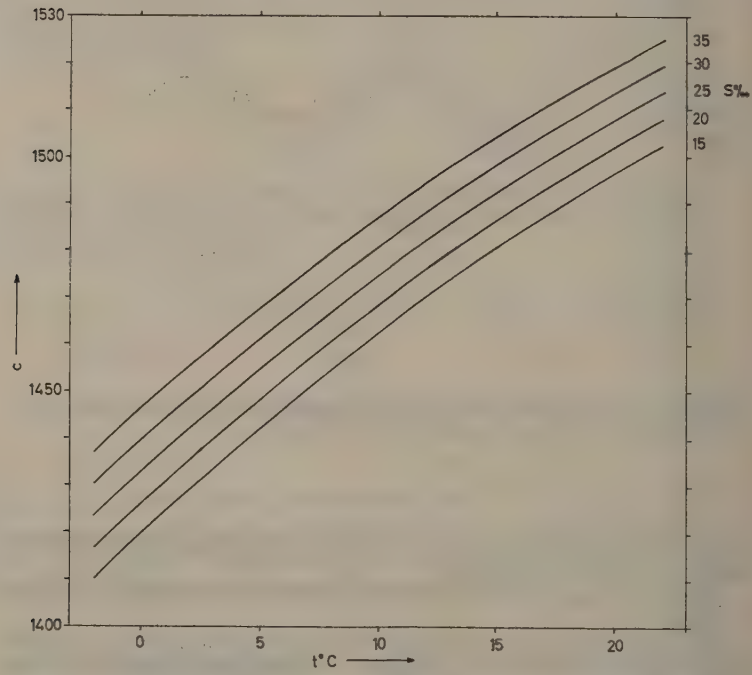


FIGURE 1.4 - Changes in sound velocity c, with changes in temperature, $t°C$, and salinity S ‰.

1.1.2 Sound intensity

Sound intensity is defined as the average amount of energy crossing unit area of a surface normal to the direction of propagation in unit time. The energy contained in a sound wave consists of kinetic energy due to particle velocity, and potential energy due to compression. It can be shown that the total energy per unit volume of water E is given by

$$E = \frac{1}{2} \rho u^2 + \frac{p^2}{2 \rho c^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

so that the amount of energy crossing unit area in unit time is given by

$$cE = \frac{1}{2} (\rho c) u^2 + \frac{p^2}{2(\rho c)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

For a plane wave, or a spherical wave sufficiently far from its source, equation (1) gives $p = Zu$, and it can be proved that

$$Z = \rho c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

so that

$$cE = \frac{1}{2} Zu^2 + \frac{p^2}{2Z} = Zu^2 = \frac{p^2}{Z} \quad \ldots\ldots\ldots (9)$$

Thus the sound intensity

$$I = \frac{\overline{p^2}}{Z} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where the bar indicates the time average of p^2. In the case of a simple harmonic wave, $\overline{p^2} = {}^1/_2 \hat{p}^2$ where $\hat{p}$ is the peak amplitude of the pressure. The factor $Z = \rho c$ is called the *acoustic impedance* of the water.

If the sound source is small compared with the distance the waves travel, it constitutes a point source, and spherical waves radiate from it in all directions. The wave fronts expand with the velocity of sound, c, and their area increases as the square of their distance from the source, as shown diagrammatically in Figure 1.5.

It follows, therefore, that the sound intensity, I, must decrease accordingly with distance from the source, and is given by the expression

$$I = \frac{1}{2\ \rho c} \cdot \left(\frac{a}{R}\right)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

where R = the distance from the sound source
a = the amplitude of the pressure wave at unit distance from the source
c = sound velocity
ρ = water density

1.1.3 Directivity of transducers

In the case of two point sources vibrating at the same frequency: if the distance between them is one wavelength and the sources are vibrating together, the waves transmitted along the line connecting them will interfere constructively and be in phase, producing a reinforced wave, as shown in Figure 1.6A. Figure 1.6B, on the other hand, shows that if the distance between the sources is one half wavelength, the two sets of waves will interfere destructively and will be out of phase. The total sound field around the two sources is illustrated in Figure 1.6C, which shows that in some directions the waves are in phase and in others out of phase.

With sonar, it is necessary to operate with directed sound, the sound energy being transmitted within a well-defined beam. This is achieved by the use of a plane, often rectangular electroacoustic oscillator (usually

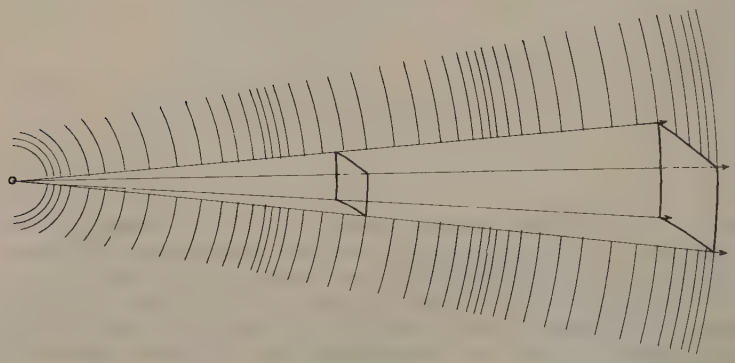


Figure 1.5 - The area of a wave front surface within a certain solid angle increases proportionally to the square of the distance from the source.

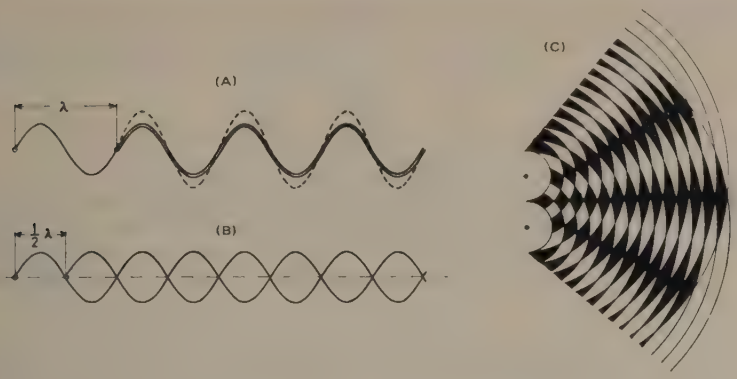


FIGURE 1.6 - Schematic illustration of interference between sound waves originating from two sound sources.

termed a transducer — see Section 2), having sides which are longer than the wavelength of the transmitted sound. The face of the transducer can be regarded as consisting of many point sound sources, transmitting in all directions. The sound waves generated by them interfere with each other so that the sound intensity varies with direction. In the direction perpendicular to the transducer surface all the waves are in phase, resulting in a maximum sound intensity in this direction, but at angles to the side of the perpendicular the sound intensity gradually decreases. At an angle θ_1, given by the relation

$$\sin \theta_1 = \frac{\lambda}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

(where L = length of the side of the transducer) the sound intensity must be a minimum, since the waves from the different point sources moving in this direction are out of phase (see Figure 1.7). At a greater angle, a weaker secondary maximum, termed a side-loop, is found, and at a still larger angle θ_2, given by $\sin \theta_2 = \frac{2\lambda}{L}$, another minimum is found.

The distribution of sound energy transmitted in different directions can be described by a *directivity pattern function*

$$b = b\ (\theta, \varphi) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where the angle θ is the angle from the perpendicular to the transducer and φ the angle from a certain reference direction within its plane, as shown in Figure 1.8. If $I\ (0, 0)$ is the intensity of sound transmitted in the

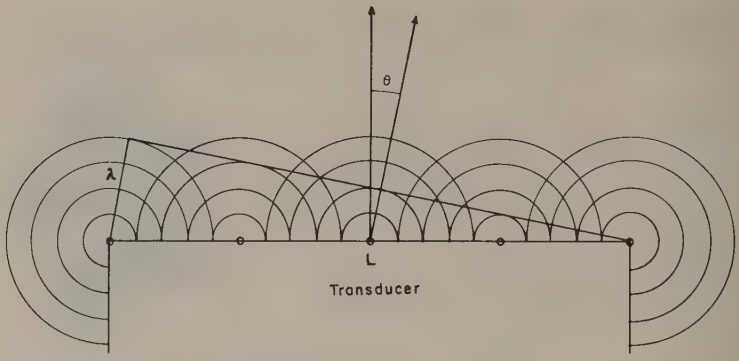


FIGURE 1.7 - Sound transmission from a transducer. At a given angle θ from the normal, there is a phase difference of π, i.e., $\frac{\lambda}{2}$ between the neighbouring point sources indicated.

direction perpendicular to the transducer, termed the *acoustic axis*, and $I(\theta, \varphi)$ the intensity in the direction (θ, φ), then

$$b = b(\theta, \varphi) = \frac{I(\theta, \varphi)}{I(0,0)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (14)$$

b is, therefore, a quantity varying between 0 and 1.

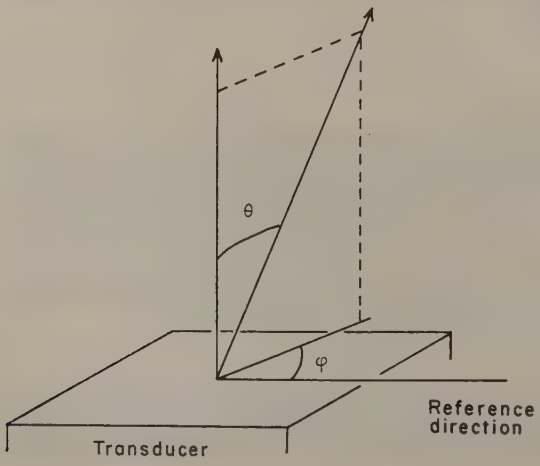


FIGURE 1.8 - Interpretation of the direction (θ, φ).

Normally the directivity pattern function has to be found empirically for each particular transducer, but a good approximation can be obtained using the equation of diffraction

$$b = \frac{\sin^2 \beta}{\beta^2} \text{ where } \beta = \frac{\pi L}{\lambda} \sin \theta$$

It is often convenient to operate in terms of amplitude of signal instead of echo intensity. This can be measured directly as voltage, because the amplitude of the acoustic signal is directly proportional to that of the electrical signal recorded in the receiver. This makes it necessary, however, to define another *directivity coefficient*, δ, which is the ratio of the amplitudes of the signal transmitted at an angle to the acoustic axis to that at the same range on that axis. It is seen from equation (11) that the echo intensity is proportional to the square of the amplitude. It is evident from equations (14) and (11) that

$$b = \frac{I(\theta, \varphi)}{I(0,0)} = \frac{\left(\frac{a}{R}\right)^2_{(\theta,\varphi)}}{\left(\frac{a}{R}\right)^2_{(0,0)}} = \frac{a^2_{(\theta,\varphi)}}{a^2_{(0,0)}}$$

Therefore $\delta = \sqrt{b}$

The directivity pattern of a transducer is often represented by a polar diagram, usually referred to the two planes parallel to the transducer sides. An example is shown in Figure 1.9.

The unit used here is termed *decibel* (dB), defined as 10 times the logarithm of $\frac{I}{I_o}$ where I_o and I are any two sound intensities.

A useful quantity to describe the directivity of a transducer is the directivity factor, or *directivity index DI* when quoted in decibels. The directivity factor is the ratio of the intensity on the acoustic axis of the beam to the intensity which would result if the same total acoustic power were to be radiated uniformly in all directions. Mathematically, the directivity index is given by

$$DI = 10 \log \frac{4\pi}{\int_\Omega b d\Omega} \quad \ldots\ldots\ldots\ldots\ldots\ldots (15)$$

and a useful approximation is

$$DI = 10 \log \frac{4\pi A}{\lambda^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (16)$$

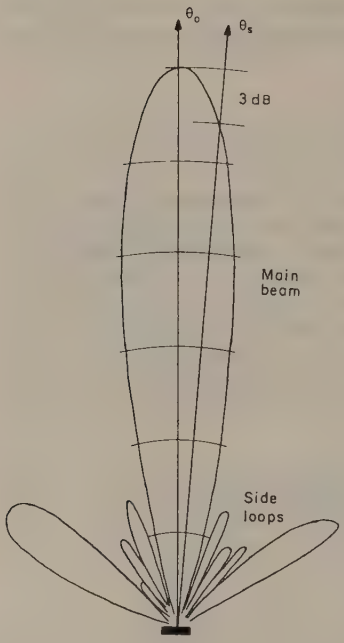


FIGURE 1.9 - A transducer's directivity diagram: θ_0 = acoustic axis; θs = half value angle.

where A is the active area of the transducer face, and λ the wavelength in the same units of measurement.

A common way of describing the width of the sound beam is to use the half value angle, θs, the angle at which the sound intensity has dropped to half the value it has on the acoustic axis, that is, the angle at which $b = \frac{1}{2}$ and $10 \log b = -3$ dB.

The sound intensity in the direction θs is thus 3 dB below that on the acoustic axis. It is possible, to a good approximation, to compute the angle θs for a rectangular transducer by means of the formula

$$\theta s = \pm 25 \frac{\lambda}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

where λ is the wavelength and L is the transducer side length in the same plane.

1.1.4 Description of the sound field

The following paragraphs sum up the properties describing the sound field and introduce the units which are convenient to use.

Sound pressure, p. Sound pressure is usually quoted in microbars, or dynes/cm^2, these two units being the same. Usually, the root mean square value of the pressure is quoted, and in the case of a harmonic or sinusoidal wave the root mean square value is $\frac{1}{\sqrt{2}}$ or 0·7 times the peak pressure.

Sound intensity, I. Sound intensity is usually quoted in watts/cm^2, and when this unit is used the intensity is given by

$$I = 10^{-7} \frac{\overline{p^2}}{\rho c} \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

where ρ is in grammes/cm^3, p is in dynes/cm^2 and c is in cm/sec.

Sound level, L. Sound level L is measured in decibels, and is defined as

$$L = 10 \log \frac{I}{I_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots (19)$$

where I is the intensity and I_0 is a specified reference intensity. I_0 is usually adopted as the intensity corresponding to a root mean square pressure of 1 dyne/cm^2, so that

$$L = 20 \log p \quad \ldots\ldots\ldots\ldots\ldots\ldots (20)$$

Source level, SL. The source level SL is a measure of the effective power of a sound source. It is defined as the sound level in decibels on the acoustic axis of a transducer referred to a point one metre from the transducer.

$$SL = 10 \log \frac{I_S}{I_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots (21)$$

where I_S is the intensity on the axis at one metre from the transducer.

Sound field level. The sound field level at any point in the sound beam can be found from the source level and directivity pattern function of a transducer. The sound intensity at a point (R, θ, φ) is given by

$$I_{(R,\theta,\varphi)} = \frac{I_S \cdot b_{(\theta,\varphi)}}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots(22)$$

where R is distance from the transducer, and θ and φ are defined by Figure 1.8.

Thus

$$L_{(R,\theta,\varphi)} = SL + 10 \log b_{(\theta,\varphi)} - 20 \log R \ldots\ldots\ldots\ldots\ldots(23)$$

The above formula is only valid in a homogenous, nondissipating medium. Since sea water is not such an ideal medium, another term must be added to the equation (23), namely the transmission anomaly.

Transmission anomaly. The transmission anomaly, A, is a quantity describing the drop of sound level during transmission through sea water additional to the geometrical spreading as described by the inverse square law. Thus

$$L_{(R,\theta,\varphi)} = SL + 10 \log b_{(\theta,\varphi)} - 20 \log R - A \ldots\ldots\ldots\ldots(24)$$

The transmission anomaly is caused by two groups of factors. The first one is called the *attenuation* of the sound due to absorption and scattering. The second is called the *spreading anomaly* and includes refraction but also reflection from boundary surfaces.

In vertical echo sounding, spreading anomaly can be disregarded and the transmission anomaly is caused by attenuation only, so that

$$A = \alpha R \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(25)$$

where α is the attenuation coefficient measured in decibels per metre, and R is the distance in metres.

The attenuation of sound in water increases with rising transmission frequency, and it also varies from place to place and time to time due particularly to changes in the scattering properties of sea water. Some average values are given in Figure 1.10.

Often the drop in sound level caused by both geometric spreading and transmission anomaly is called the *transmission* or *propagation loss*, H, which is therefore given by

$$H = A + 20 \log R \ldots\ldots\ldots\ldots\ldots\ldots\ldots(26)$$

Spreading anomaly becomes important in horizontal echo ranging, due to the refraction of the sound beam. It has already been shown that the velocity of sound varies with temperature, salinity and depth. The greatest variations of sound velocity are caused by variations in temper-

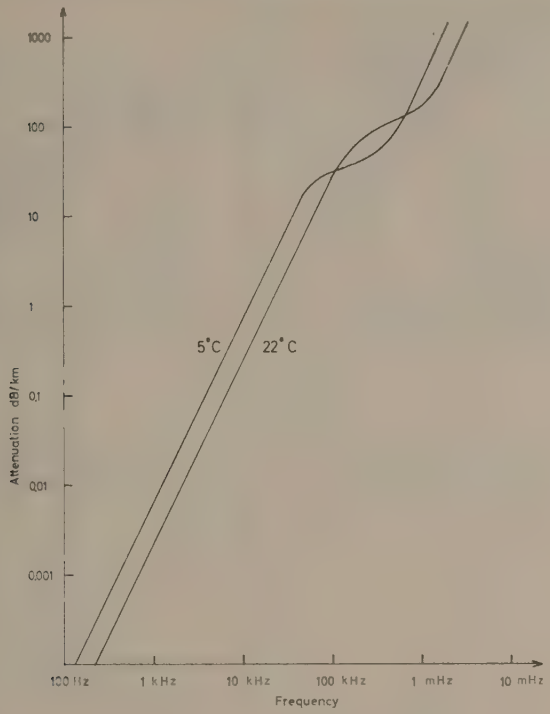


FIGURE 1.10 - Changes in the attenuation coefficient for sound in the sea, with increasing transmission frequency at 5°C and 22°C.

ature, which are often rather large vertically. If the velocity of sound decreases with depth, the upper part of a wave front will travel faster than the lower part. This will cause the advancing sound beam to be deflected, as shown in Figure 1.11. In the same way a positive velocity gradient results in an upward deflecting beam.

If the beam angle of sound transmitted from a horizontal echo ranger and the variation with depth of the sound velocity are known, it is possible to compute the sound field conditions. Four typical transmission patterns, constructed from measured velocity conditions in a locality off the coast of Norway, are shown in Figure 1.12.

In and below a temperature discontinuity the transmission anomaly A will be large, resulting in poor sonar conditions. This is known as the *layer effect*.

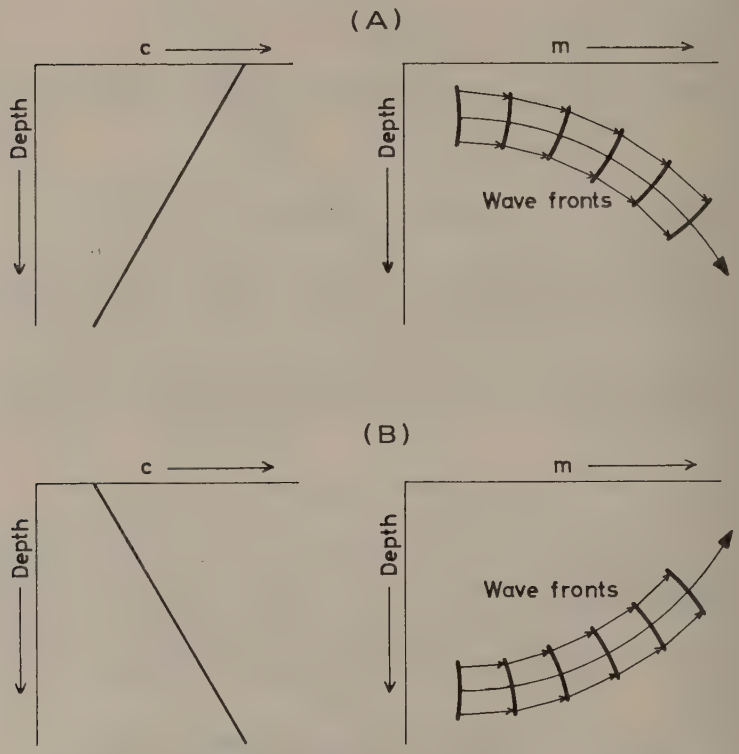


FIGURE 1.11 - The refraction of a sound beam: (A) = velocity decreasing with depth; (B) = velocity increasing with depth.

1.2 Reflection of sound in water

If a man shouts against a steep cliff or mountainside he gets an *echo* because the sound of his voice is reflected from the wall and reaches his ears. When the sound waves reach the wall, the wall obstructs the movements of the air particles. The wall exerts a counter pressure on the vibrating air particles equal to the pressure of the particles on the wall. In fact, the wall itself becomes a source of sound, transmitting sound waves counter to those reaching it. These waves transmitted by the wall constitute the *reflected sound.* The whole process may be compared to what happens when a rubber ball bounces back from a brick wall.

In a similar way sound is also reflected in the sea by the seabed, and other targets such as fish or shoals of fish.

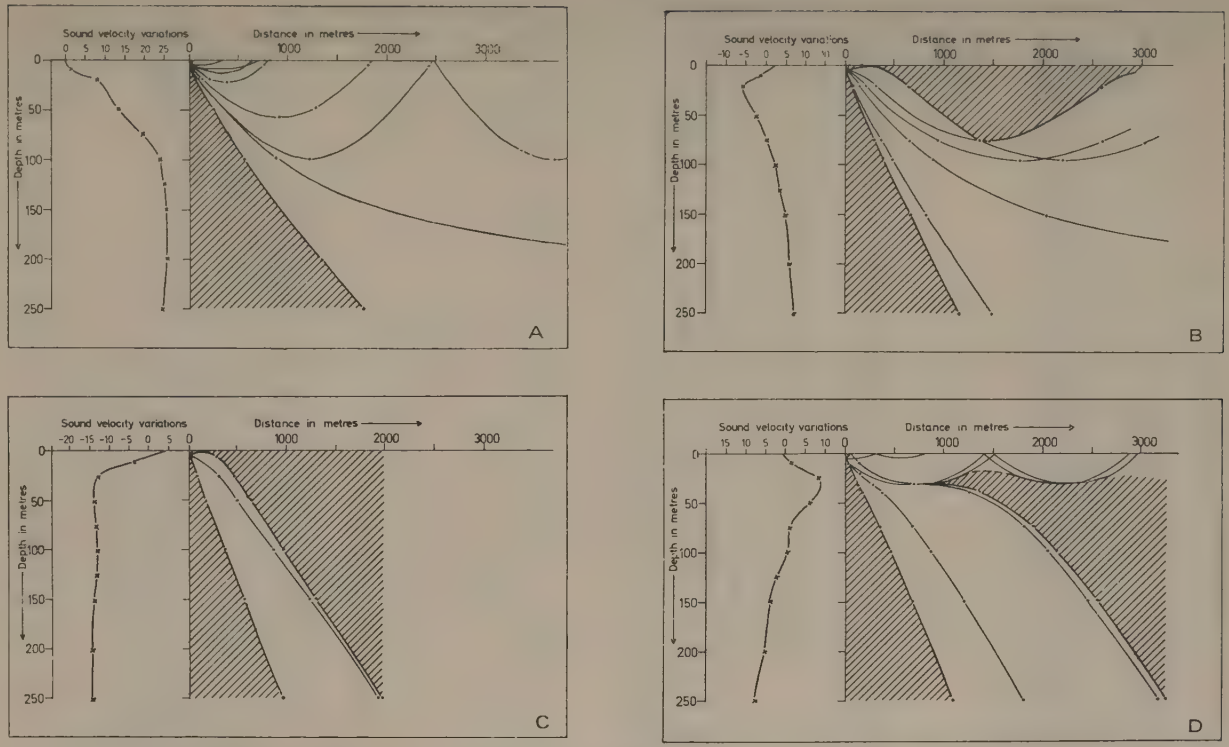


FIGURE 1.12 - Four typical sound-beam transmission patterns computed from measurements of temperature and salinity. Beam half value angle, $\theta_S = \pm 12.5°$. Shadow zones are hatched.

1.2.1 Echo level

When sound is reflected by a target, the intensity of the reflected sound, I_e, is proportional to the intensity of the incident sound I_i. If the reflected sound intensity is measured at a distance R from the target, according to the inverse square law

$$I_e = k \frac{I_i}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots (27)$$

where the value of the coefficient k depends on the nature of the target. The same formula expressed in decibels is

$$10 \log I_e = 10 \log k + 10 \log I_i - 20 \log R \quad \ldots\ldots\ldots (28)$$

However, as has been shown for the transmitted sound, this formula is valid only in a homogenous, nondissipating medium, and when applied to the sea account must be taken of the losses due to attenuation as well as those for geometric spreading: that is, the 20 log R of equation (28) must be replaced by the transmission loss, H. Therefore

$$10 \log I_e = 10 \log k + 10 \log I_i - H \quad \ldots\ldots\ldots\ldots\ldots\ldots (29)$$

The level of incident sound can be found from equations (24) and (26) and the level of the reflected sound, from a direction θ, φ, called the *echo level*, $EL_{(\theta,\varphi)}$ is therefore given by

$$EL_{(\theta,\varphi)} = 10 \log k + SL + 20 \log b_{(\theta,\varphi)} - 2 H \quad \ldots\ldots (30)$$

1.2.2 Target strength

The quantity 10 log k in the above equations is called the *target strength*, *TS*, and is dependent on the size and other characteristics of the target. The reflection strength of the target can also be expressed by another quantity, called the effective target area or *scattering cross-section*, σ, and defined as follows:

"If an echo were reflected by a total reflecting target with uniform spherical reflectivity pattern, the area of this target normal to the incident sound would be equal to σ."

TS and σ are related by the expression

$$TS = 10 \log \frac{\sigma}{4\pi}; \qquad \text{where } \frac{\sigma}{4\pi} = k \quad \ldots\ldots\ldots\ldots (31)$$

It is seen that a totally reflecting sphere of radius 2 metres has a target strength of 0 decibel, because the scattering cross-section of this sphere is equal to 4π. The target strength of an object depends on several factors:

The acoustic impedance of the target in relation to that of water expressed by the *index of reflection*, μ

$$\mu = \frac{Z_1 - Z_2}{Z_1 + Z_2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (32)$$

where $Z = \rho c$ is the impedance and 1 and 2 indicate water and target, respectively.

The size of the target in relation to the wavelength of sound. If the size is described by a parameter, l, and the wavelength by λ, one can distinguish between three magnitudes of this relation:

when $\lambda \ll l$ the target strength can be found by using laws of geometric optics;

when $\lambda \gg l$ (the so-called Rayleigh scattering zone) the scattering cross-section can be shown to vary inversely with the fourth power of the wavelength;

in the intermediate zone where wavelength and target size are similar, the target strength is dependent on the size, geometry and orientation of the target.

The sizes of most fish of interest in this type of study are within the range of 10 to 100 centimetres. Since at very low frequencies (<10 kHz) the noise level is often too high, and at very high frequencies (>100 kHz) the attenuation is high for general fish detection purposes, it is the middle zone of frequencies that is usually chosen for equipment. Theoretically the target strength of a given fish should increase with frequency, but there are not yet enough observations to establish the relationship between target strength and fish size, at different frequencies.

The transition between the Rayleigh zone and the middle zone takes place when the dorsal-ventral dimension of the fish (which at its maximum is approximately 0.2 of the total length) approaches that of the wavelength (Haslett, 1962). Figure 1.13 shows the relation between the scattering cross-section and frequency in the two zones for fish of 90, 45 and 22.5 cm length. The data, which are taken from Haslett (1962b and 1964) show that entry into the middle zones is characterized by a series of maxima and minima, the trend of the maxima being indicated by the broken line.

The pulse length of the transmitted sound is of importance only when the length of the pulse in water τc is small compared to the target size.

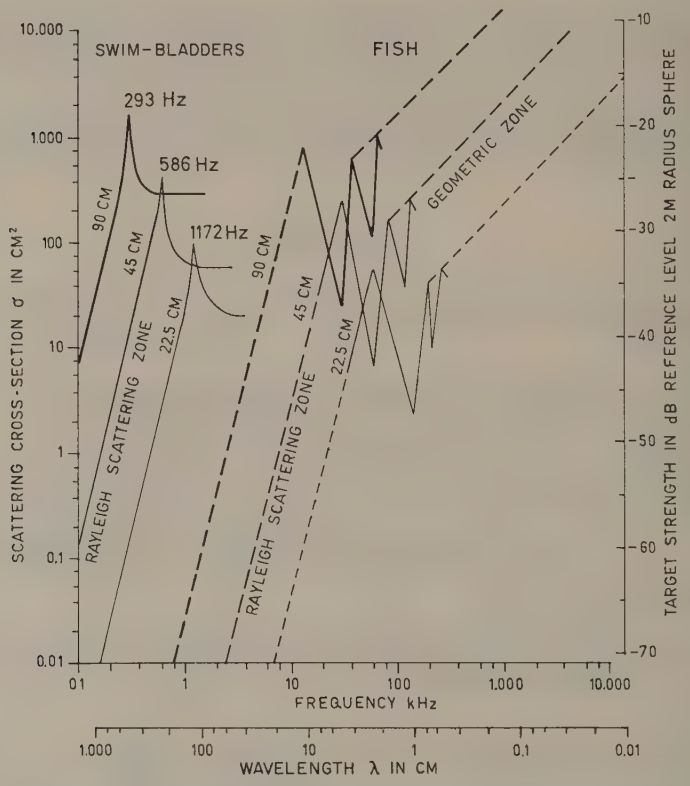


FIGURE 1.13 - The relationship between target strength and transmission frequency for fish of 22.5 cm, 45 cm and 90 cm length respectively.

1.2.3 TARGET STRENGTH OF FISH

Although some direct measurements of target strengths of fish have been made, considerably more data are needed in order to establish a satisfactory law for sound reflection by fish of different species and size.

Measurements of target strength have been made by Hashimoto and Maniwa (1956), Midttun and Hoff (1962), Cushing (1963), Shishkova (1963) and Lowe (1969, 1971). The measurements obtained are very variable but those of Midttun and Hoff (1962) show the relation between target strength and length of fish most clearly. In their experiments, the fish were kept alive at testing depths for a week and then killed just before the measurements were made. Figure 1.14, reproduced from Cushing

(1964), summarizes some of the measurements obtained by these and other workers (Harden Jones and Pearce, 1958; Cushing, 1963).

It will be seen that as fish length increases its target strength increases as nearly the cube of the length, indicating that it bears some relation to the volume of the fish. But the relation is not a simple one, due to the different sound-reflecting properties of different parts of the fish. The signal is returned in varying proportions from bones, flesh and air bladder (Haslett, 1962). Harden Jones and Pearce (1950) and McCartney and Stubbs (1971) have shown that the swim-bladder is responsible for about half the signal returned from those species of fish which possess one. Also the target strength varies with the aspect of the fish, the lateral aspect returning ten times as much signal as the dorsal aspect under some conditions (Harden Jones and Pearce, 1958; Haslett, 1964). However, at any intermediate aspect there are a number of minima, differing with sizes and species of fish (Haslett, 1962; Midttun and Hoff, 1962). Haslett (1964, 1970) provides a good summary of the physical basis of echoes received from fish targets.

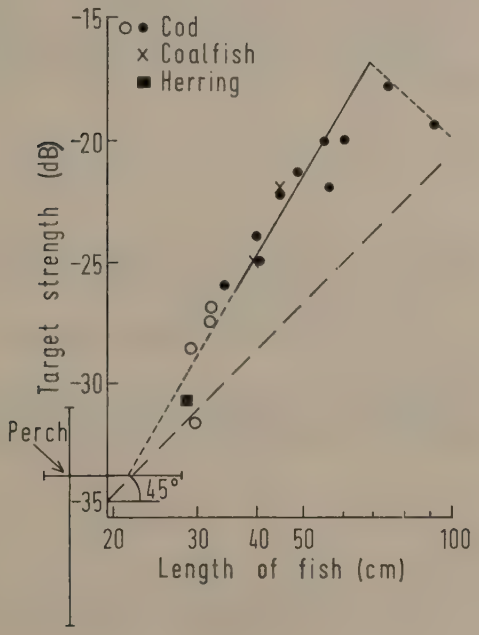


FIGURE 1.14 - Measurements of target strength of cod, coalfish and herring; after Cushing, 1964.

McCartney and Stubbs (1971) recommend the equation

$$TS = 24.5 \log_{10} L - 4.5 \log_{10} \lambda - 26.4 \quad \ldots\ldots\ldots\ldots\ldots\ldots (33)$$

(L = fish length in metres, λ = wavelength in metres) to be used when sizing fish by target strength measurements with calibrated echo sounders at sea. However, as Figure 1.14 and equation (33) both show the relation between the maximum dorsal aspect target strength and fish length they will both tend to undersize the fish when used at sea. This is due to the variation of target strength with fish aspect and the spatial orientation of the fish (Midttun and Nakken, 1971).

Many fish of commercial importance have swim-bladders, occupying about 7 and 5 percent of body volume in freshwater and marine species respectively, which can enhance the echo to give scattering cross-sections much greater than those which would be observed in their absence. There is also the possibility of an added bonus by way of resonance. If the swim-bladder is regarded as a spherical bubble, its scattering cross-section can be considered as having three major regions. At low frequencies, the Rayleigh scattering, or fourth power law, is obeyed: at resonance the scattering cross-section is independent of bubble size, and at higher frequencies the scattering cross-section, σ, is independent of frequency and equal to the bubble surface area; i.e. $\sigma = 4\pi R^2$.

The resonant frequency of the swim-bladder can be determined from the formula

$$f_r = \frac{1}{2\pi a} \sqrt{\frac{3\gamma P_o}{\rho}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (34)$$

where a = radius of a sphere of same volume as the swim-bladder
γ = ratio of specific heats of gases
ρ = density of water
P_o = the ambient pressure in dynes/cm²

Weston (1961) gives a simpler formula from which the resonant frequency of a swim-bladder can be calculated for a fish of given length and living at a given depth (or pressure). In Weston's formula

$$f_o L = 8 \sqrt{P_o} \quad \ldots\ldots\ldots\ldots\ldots\ldots (35)$$

where f_o = resonant frequency in kHz
L = fish length in cm, and
P_o = ambient pressure in atmospheres

Weston (1967) also gives a simple formula to calculate the scattering cross-section of the swim-bladder in the region above resonance, where the values are more or less independent of frequency, depth and various sources of loss. In this formula $\sigma = 4 \times 10^{-2}L^2$ giving, for 90, 45 and 22.5-cm fish, scattering cross-sections of 320 cm^2, 80 cm^2 and 20 cm^2 respectively.

There is some uncertainty as to what increase in scattering cross-section might be obtained from the swim-bladder, at resonance, within the body of the fish.

Scattering cross-sections of swim-bladders for 90, 45 and 22.5-cm fish are included in Figure 1.13, the resonance frequency being calculated for a depth of 50 fathoms. The scattering cross-section at resonance has been taken as five times that in the region above resonance. These values are only estimates, but they do serve to show the increase in scattering cross-section that could result from the presence of the swim-bladder.

SECTION 2. THE STRUCTURE AND FUNCTIONING OF SONAR EQUIPMENT

2.1 Basic features of sonar equipment

A sonar system comprises the four basic units shown diagrammatically in Figure 2.1.

In this diagram, block 1 is the time-base and display unit. Block 2 is the transmitter which is connected to block 3, the transducer. From this, received signals go to block 4, the receiver amplifier, and from it to the display unit. The time-base and display unit may be an electric motor driving a mechanical system for marking a recording paper, or an electronic circuit controlling the speed at which a spot of light travels across the face of a cathode-ray tube. In either case accuracy of timing is important, for an error of $\pm 1.5 \times 10^{-3}$ sec would give a depth or range error of $\pm$ 1 m.

At one point on its travel the stylus arm on the mechanical system, or the spot on the cathode-ray tube, will pass the zero mark on the depth or range scale, and at this instant of time the transmitter (block 2) is switched on by the time-base and its energy is released to the transducer (block 3). The transducer converts electrical energy to acoustic energy which is propagated through the water. In most modern equipment the same transducer receives the echo from a distant object or seabed, converting it back from an acoustic to an electric signal.

It has been shown in Section 1 that the echo has only a fraction of the energy of the transmitted pulse. The receiver amplifier (block 4) is necessary to increase this weak signal by perhaps 10^6 times to mark the recorder paper or deflect the cathode-ray tube spot.

While the basic principles underlying the vertical echo sounder and the horizontal echo-ranging sonar are essentially the same, the two types of equipment differ in some important respects. Therefore, in the following description of the features and functioning of the main units as defined above, attention is first paid to the echo sounder. The special features of sonar are then described.

2.2 Echo sounder

2.2.1 The paper recorder

Although there are many types of recorder available, they all have two main functions: to trigger the transmitter and to record the echo signals.

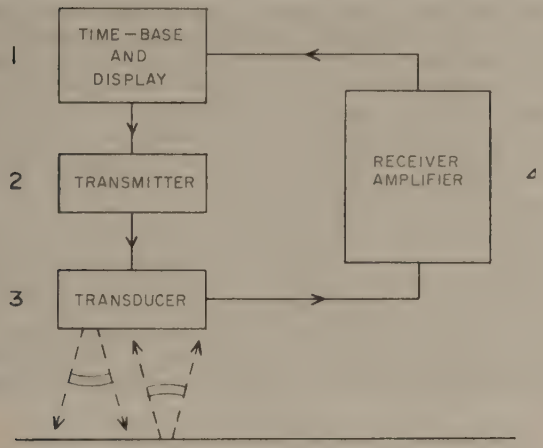


FIGURE 2.1 - Block diagram of basic echo sounder system.

For many years these recorders have used a system where the stylus is attached to a moving arm or belt and traverses the surface of an electrosensitive paper. The echo signals pass through a slipring system to the stylus and thus to the recording paper.

There are two types of paper, wet and dry. The wet paper is more sensitive, it shows weak signals well. It also has greater dynamic range, that is, the ability to show different degrees of colouring according to the signal strength. However, the recordings fade quickly and the whole paper eventually turns white if stored in contact with light and air. Some shrinking of the paper occurs when drying out. Care is needed in the storage of unused wet paper rolls so that they do not spoil. They should lie on their sides in a cool place, be turned regularly, and stored for the shortest possible time.

Stylus pens used for wet paper are thicker than those for dry paper; they also have a polished tip. The speed of the wet-paper stylus is limited if satisfactory marking is to be obtained. Maximum stylus speed corresponds to about 100 m depth scale across a 15-cm wide paper.

Dry paper has an electrically conducting reverse surface. This is in contact with the metal plate over which it is drawn. When a signal is received, the voltage between the fine wire stylus and the metal plate has to rise to such a value that breakdown of the paper's front surface occurs. A black mark is thus burnt on the paper (which is normally grey).

With some recorders it is possible to change from one type of paper to the other by changing the stylus and operating a switch to adjust the echo signal voltage levels.

There are two types of wet-paper recorder which do not use a stylus rotated on a moving arm or belt. In the first, the helix recorder, the stylus is a wire or metal blade wound in the form of a helix and supported on the surface of a drum or a metal frame. The wire or blade turns through approximately 360° from one end of the drum (which is the same width as the paper) to the other. A fixed straight blade, or slowly moving continuous loop, forms the electrode on the side of the paper opposite to the helix wire. As the drum rotates the helix wire becomes, in effect, a small point running across the paper.

The other is the multistylus recorder, a relatively new development, in which hundreds of wires are aligned like the teeth of a comb and placed in permanent contact with the paper. Each wire, or stylus, receives signals separately from its associated electronic circuit. The styli are scanned electronically at the required speed, which can be very fast so that scale expansion is greatly facilitated, for example, 19 m across 15 cm width. Such a system can easily be adapted to provide a seabed locked display.

2.2.1.1 *Trigger contacts*

The switching or trigger contacts for the transmitter are usually operated from the same rotating system as that of the stylus arm, belt, or helix. In the case of the multistylus recorder a synchronized electronic switch is used.

2.2.1.2 *Ranges and paper drive*

For the basic ranges of the echo sounder the trigger contact operates each time the stylus passes the zero point of the depth scale. The basic ranges are changed by altering the speed of rotation of the stylus, either by selecting different gearbox ratios or by switching the motor speed. A combination of these two systems can be used to give maximum choice of ranges. Normally the paper-drive system is coupled to the stylus drive by reduction gears, and paper speed changes in proportion to stylus speed. Typical basic ranges for paper recorders are 125, 250 and 500 m for full paper width.

2.2.1.3 *Phasing*

A useful feature on many of the moving-arm recorders is the phasing system. This is shown diagrammatically in Figure 2.2 and can be used in the following way. Supposing that recordings of echo traces are required with the best possible resolution between 220 and 330 m depth: if the speed is changed so that the depth scale is 0 - 330 m, the traces of interest would be compressed into half the paper width. But, using the phasing system, the contacts marked 220 - 330 m can be selected to trigger the transmitter so that it operates at a time corresponding to 220 m before the stylus passes the scale zero. Then, provided that the recorder is running on the 0 - 110 m range, the full paper width will show traces between

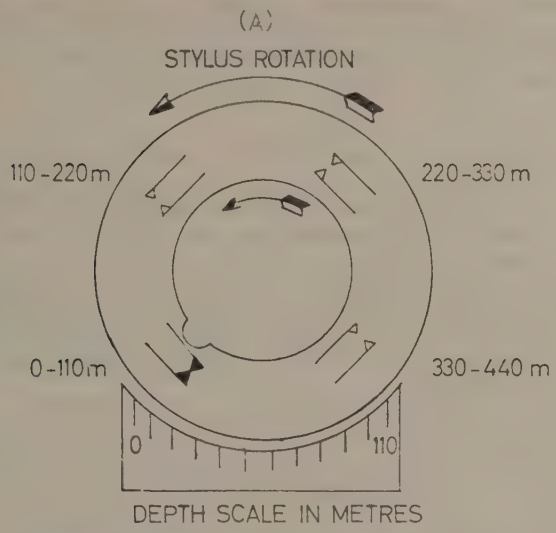


FIGURE 2.2 - Method of extending the depth of the recorder scale by phasing.

220 to 330 m. Because the recorder is running at the 0 - 110 m rate the paper speed will be high, so that echo traces will be expanded along the length of the paper in addition to the depth scale expansion.

2.2.1.4 *Calibration of paper length*

Some method is needed to calibrate the length of the record. This can be done in a number of ways, the simplest being to mark the paper to indicate a definite time interval. This can be either a short mark at the edge of the paper or extended over the whole width. For echo surveys a more useful reference mark is the nautical mile. This can be arranged by taking a suitable output from the ship's log.

2.2.2 POWER SUPPLY

Most small ships have difficulty in maintaining a completely steady power supply, due to the relatively low capacity of their generators and fluctuation of the loads throughout the ship. Some ships have direct current (DC) and others alternating current (AC). Recorder motors are now usually largely independent of power changes. They depend for their accuracy on the frequency (cycles per second or Hz) of the power

supply. The AC for these motors is usually taken from a separate system of an automatically regulated motor driving an alternator. Arrangements are made in the receiver-amplifier and transmitter circuits which prevent power supply changes from having any serious effect.

2.2.3 Cathode-ray tube (crt) system

Cathode-ray tubes are used for both vertical echo sounders and horizontal sonars, their advantage over the mechanical paper recorder being that a greatly magnified portion of the water column can be displayed. This is because the picture results from an electron beam striking the tube face and causing the phosphor to glow. The electron beam can be easily deflected at a very fast speed indeed, whereas the stylus of a mechanical recorder cannot. Figure 2.3 shows a block diagram of a cathode-ray tube display.

The time-base generates a sawtooth wave synchronized by the trigger pulse. The sawtooth wave is a steadily increasing voltage which sharply returns to zero at the required time. When such a wave is applied to the metal plates, Y, Y in the tube, the electron beam which is focused on to its face will be deflected by the electrostatic field. This linear deflection forms the time-base. Signals from the transducer are amplified and applied to the plates X, X. Because they are still alternating either side of zero voltage, at the frequency at which they were transmitted, the spot will be deflected proportionally on the tube. Thus, for small voltage signals the spot does not travel as far as for large signals, and the smaller ones will therefore appear brighter. The phosphor is chosen so that the light decays quickly and avoids trace-to-trace correlation which might be confusing.

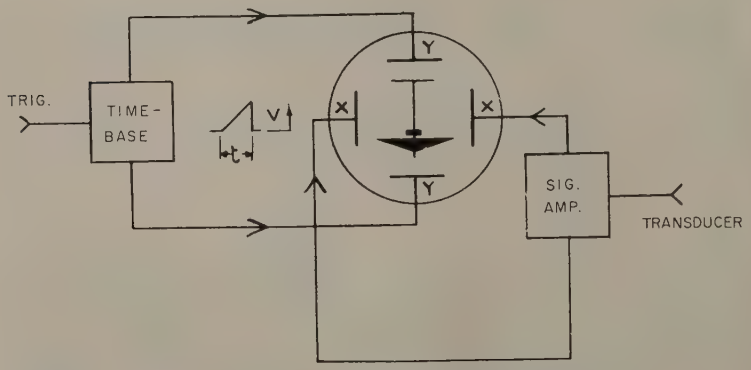


Figure 2.3 - Block diagram of cathode-ray tube time-base display system.

There are three main ways in which the cathode-ray type displays are used:

as a slave to a paper recorder;

as a time-base and display for full sea-water depth or full range of horizontal ranging;

as a plan position indicator display for horizontal ranging (described in the sonar section).

The block diagram in Figure 2.3 applies to the first two uses. In the simplest version of the slave system the trigger input comes from the paper recorder obtained from a switch contact. Thus any portion of the water column may be selected by moving the pointer until it corresponds with the required depth or range marking on the scale. The time-base for this system is made to run at a speed corresponding to a sound-path-length in water of around 10 m. This portion of the water column is shown across the full width of the cathode-ray tube, which may vary from 7.5 to 15 cm.

Another slave system uses the transmission pulse as a time reference. Electronic circuits then provide time delays from this reference which can be made to correspond to any required depth or range. At this point, a further pulse is generated to start a time-base running at a sweep speed corresponding to 10 m, as above, giving a similar display. In this case, the time-base is made to start at the time of transmission and finish at the maximum depth or range required. This is useful when no particular depth or range has to be monitored. When small echoes appear, it is usual to switch to a fast time-base (10 m). By using a variable delay unit, the fast time-base can be positioned over the small echoes, which can then be examined in detail.

2.2.4 Transmitter unit

Transmitters provide electrical power to the transducer when the trigger contact is operated or when a trigger pulse is generated by an electronic circuit. The following requirements must be met:

constant power output
constant frequency
controlled pulse length

Figure 2.4 shows a block diagram of the transmitter for an echo sounder or a horizontal echo-ranging system. In some cases the operation of the top three blocks is combined in one circuit. Two vacuum tubes, or two or more transistors, are connected in such a manner that they oscillate at the correct frequency for the pulse length τ and the peak voltage V_o when triggered.

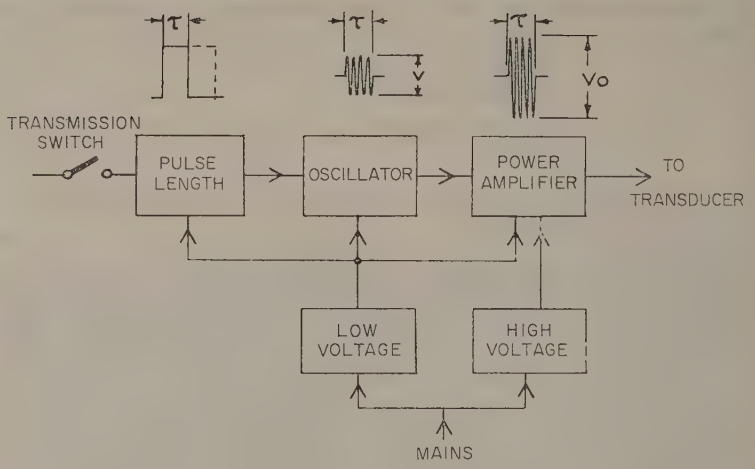


FIGURE 2.4 - Block diagram of transmitter unit for echo sounder or horizontal echo-ranging sonar.

Pulse length can often be varied, either by switched positions, or continuously between typical limits of 0.3 to 2 milliseconds for echo sounding (1 to 30 milliseconds for horizontal echo ranging).

Frequency is fixed, or is within about 1 kHz of the transducer resonant frequency, and may be adjusted.

For constant power output the supply voltages to the power amplifier tubes or transistors must remain at the correct level. The tubes and transistors must be in good condition. Most present day echo sounders have electrical peak power outputs of between 250 W and 1.5 kW. The tubes or transistors that supply this power can only do so in pulse form; they would be quickly destroyed if switched on continuously. High voltages of 1 kV or greater are used for the vacuum tube output circuit. *This is very dangerous if touched.* Voltages in the transistor power output stages rarely exceed 100 V.

Figure 2.5A represents the vibrations of the face of the transducer, transmitting at a frequency of 30 kHz at a pulse length of 0.5 millisecond. The period for 1 cycle of a 30-kHz wave is 33.3 μ sec; thus 15 cycles are produced for the 0.5-millisecond pulse length. In Figure 2.5B the resulting sound pulse shows that in the 0.5-millisecond period, 15 sine-waves, each having a wavelength of 5 cm, would be produced, the length of the wave-train being $15 \times 5 = 75$ cm. Initially the amplitude of the transmitted pulse is low, due to the acoustic impedance, but it quickly builds up to maximum amplitude.

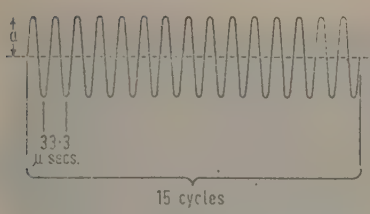


FIGURE 2.5A. - Vibrations on the face of transducer for a 0.5-millisecond 30-kHz pulse.

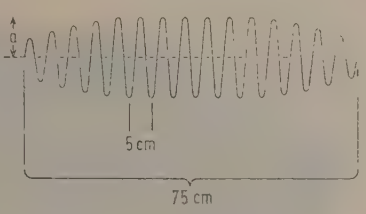


FIGURE 2.5B. - Resulting sound pulse.

2.2.5 TRANSDUCERS

The most commonly used transducers at present are magnetostrictive. Such transducers are made from a material (usually nickel) which expands and contracts according to the strength and direction of the magnetic field resulting from the applied electrical pulse. These dimensional changes cause pressure variations when the transducer is in water.

Efficiency of energy conversion, from electrical to acoustic power, is between 25 and 50 percent. For 1 kW electrical power input a typical source level for a transducer measuring 9 × 15 cm is 110 dB//1 μ Bar ref. 1 m.

The construction of magnetostrictive transducers is simple and robust (Figure 2.6). Laminations are stamped out of the nickel and treated so that they will be in poor electrical contact with one another. This avoids what is known as eddy current loss, caused by circulating currents induced in large volumes of metal. Holes stamped in the laminations carry the heavily insulated wire which couples the electrical energy into the transducer.

To obtain maximum efficiency, the nickel must be working at a suitable point on its magnetization curve. It is possible to arrange this by passing a DC current continuously through the winding, the pulse being superimposed. A more convenient method is to put slots in the laminations, so that small ceramic-type permanent magnets may be inserted. These are found in the top and sides of many transducer units.

It is very important that the transducer should be coupled into the seawater medium efficiently, and for this reason paint and grease are always carefully removed from the outer surface. If a bubble stream crosses the face, this also decouples the transducer and power is not transferred well.

The magnetostrictive transducer is used from low frequencies up to about 100 kHz. An increasing number of echo sounders are, however, now being used at higher transmission frequencies, and for their transducers it is necessary to use other materials: those coming into regular use are barium titanate and lead zirconate titanate. The characteristic they exhibit

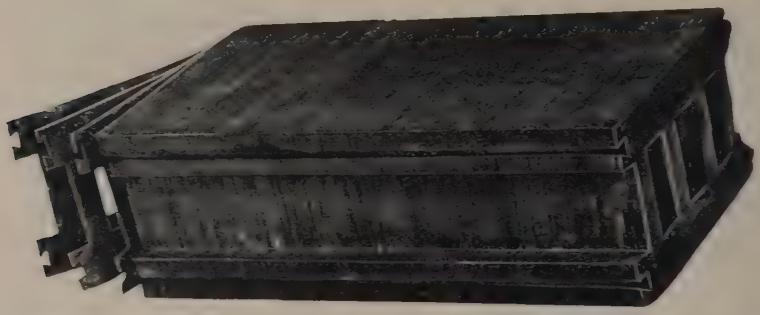


FIGURE 2.6 - Example of a magnetostrictive nickel transducer, with windings removed and some laminations pulled away to show the construction.

is known as the "electrostrictive effect," which, in simplest terms, means a change of dimensions related to the applied electric field. Before use, the elements (consisting of material moulded into the required shape) must be polarized, and this is achieved by placing them in a strong electric field; electrodes, usually silver, are then applied to the necessary surfaces.

Because the surfaces of the electrostrictive transducers cannot be in direct contact with sea water (this would short-circuit the element and remove the electrode material), an assembly is required which will provide good electrical insulation and efficient acoustic coupling to the sea. If transducers are made from large blocks of the electrostrictive material (10 to 100 cm^3), they can be mounted on a pressure release material and encapsulated in epoxy resin, as illustrated in Figure 2.7.

More efficient forms of electrostrictive transducers are available which use small slices of the material sandwiched between critically dimensioned

FIGURE 2.7 - Example of an electrostrictive-type transducer assembly. The barium titanate element is the white section in the centre.

metal parts. Protection of the connexions from sea water is obtained by using O-ring seals fitted to the metal parts.

For echo sounding at frequencies between 20 and 50 kHz, it is unlikely that the face of the transducer will be greater than 30 × 30 cm. The method of fitting the assembly into the ship varies, but in general two methods are favoured: limpet mounting or inserted mounting.

With limpet mounting the transducer assembly is completely external to the ship and only the wires pass through a gland in the hull. This allows a wider choice for positioning, and in some cases avoids the turbulence close to the hull. When fitting transducers to a ship it is necessary to ensure that the face is at such an angle to the keel that, when the vessel is in normal trim in a calm sea, it is tilted 3° forward relative to the sea surface in order to reduce turbulence and propeller interference. The limpet housing is usually shaped so that it presents least resistance to the water flow in the fore and aft direction.

An inserted mounting uses a steel housing which has walls as thick as or thicker than the ship's plating at the point of insertion. Figure 2.8 shows typical installations of both methods.

It is usual for the magnetostrictive transducer to be rectangular rather than square. The half-angle beam-width to half-power points of such a transducer is approximately $\sin \theta = 0.44 \frac{\lambda}{l}$ where λ = wavelength in water and l = length of the transducer face. The largest axis is fitted fore and aft, thus giving the narrowest beam in this direction, typically 6 to 20°. The beam-width in the other direction is likely to be between 14 and 30°.

There are a number of advantages in fitting transducers to so-called "towed bodies." These are:

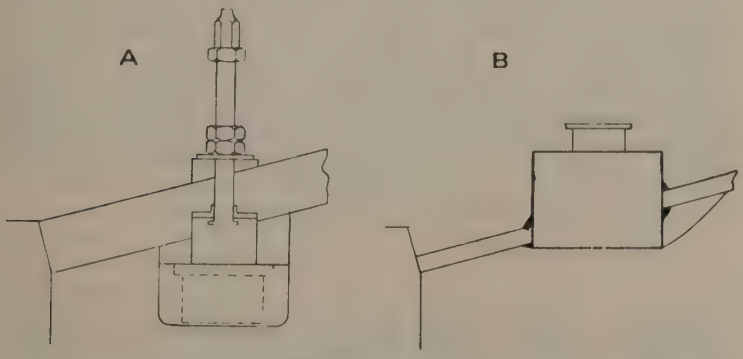


FIGURE 2.8 - Diagrammatic representation of transducer mounting: (A) limpet mounting; (B) inserted mounting.

The transducer will be free from the aeration normally associated with the hull of a ship.

Some degree of stability is gained in bad weather relative to a ship-mounted transducer.

Pick-up of ship noise on the transducer can be minimized.

The transducer may be lowered to considerable depths if required; this helps to overcome loss at high frequencies when deep fish detection is required.

2.2.6 Receiver-amplifier

Echo signals received at the transducer terminals may be very weak, sometimes only a few microvolts. Before they can be used for marking a paper record or deflecting the spot of a cathode-ray tube, they must be increased in amplitude by perhaps 10^6 (120 dB) or more. This is achieved by means of the receiver-amplifier, shown diagrammatically in Figure 2.9.

The simplest amplifier for an echo sounder can be divided into three main parts. A high-frequency section, a detector or rectifier, and the paper-marking amplifier. The high-frequency amplifier is tuned to the frequency of resonance of the transducer, signals are converted from high frequency to DC pulses by the detector. These DC pulses are changed by the paper-marking amplifier into a suitable form to match the recording paper. Transistors are now widely used for these functions.

2.2.6.1 *Band-width*

The amplifier must maintain a good signal-to-noise ratio. This means that during the amplification process the noise produced by the electronic circuits added to the noise received at the transducer terminals must not approach or exceed the echo signal level.

An important consideration in respect of noise is the receiver band-width. As the band-width increases so does the final noise voltage. However, if the received echo-pulse signal is to be reproduced without serious distortion, a minimum band-width must be given which is related to the transmitted pulse length approximately by

$$\text{Band-width in kHz} = \frac{1}{2 \times \text{pulse length}} \quad \text{(milliseconds)}$$

Band-width is usually defined as the number of cycles (or Hz) between the points on a receiver voltage/frequency response curve where the voltage is 0.707 of the maximum, that is, the 3 dB points. Thus, a typical receiver working at a nominal 38 kHz might have a gain of 10^6 at this frequency for a particular setting of the gain or sensitivity control. If the transmitted

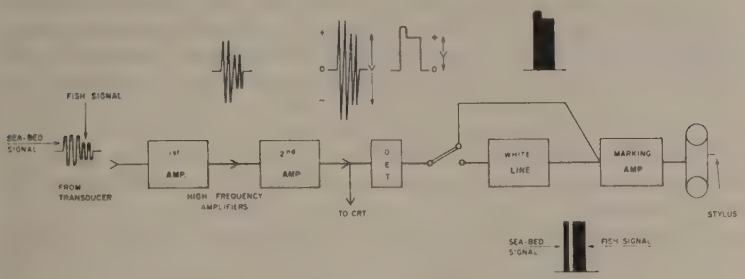


FIGURE 2.9 - Block diagram of receiver amplifier.

pulse length is 0.3 millisecond the approximate formula for band-width gives a figure of 1 600 Hz. This means that at 37.2 kHz and 38.8 kHz the gain would be 0.7×10^6.

In some echo sounders and horizontal echo-ranging systems the transmitted pulse length can be varied as mentioned in 2.2.4. It is obvious from the band-width equation that if pulse length is varied the band-width should be automatically adjusted. As the pulse length is increased to give higher average power into the water, the receiver band-width may be reduced, thus improving the signal-to-noise ratio. If a short pulse is used for high resolution, the band-width must be increased.

2.2.6.2 *Gain control*

Manual gain control is fitted to most echo sounders. It can be continuously variable or switched, but should always have some form of scale behind the knob for reference or calibration purposes.

More sophisticated amplifiers are now available with an automatic form of gain control known as time-varied-gain (TVG). This is arranged so that the gain of the receiver-amplifier starts from a very low level at the instant of transmission. It rises according to a particular law, the choice of which is discussed elsewhere in the manual. For every transmission, therefore, compensation is made for the two-way loss of signal due to geometrical spreading and the frequency-dependent absorption. Targets at different depths, but with equal target strength and located at the same angle to the acoustic axis, will therefore show equal signal deflection on an oscilloscope or CRT.

2.2.6.3 *Initial suppression*

When the transmission pulse passes into the receiver-amplifier, it is usually reduced to a safe level. However, with the receiver at a high gain setting, reverberation may be considerable for the first few metres of water under the ship. To reduce this effect the transmission pulse causes a voltage

to be developed across a capacitor in the input circuit, which reduces the gain of the amplifier. The effect is arranged to die away quickly and is dependent upon the time constant of capacitance and resistance in this part of the circuit. Such a system is unnecessary if TVG is being used.

2.2.6.4 *White- or black-line recording*

These descriptions apply to the same technique, so the term *white-line* will be used here.

When looking for fish concentrations close to the seabed, it is often difficult to distinguish fish echoes from seabed echoes. This is because the resolution of the echo sounder is not sufficient to separate these echoes. There is usually a great difference in signal strength between them (see Figure 2.9) and it is this factor which allows the white-line system to function. An extra circuit is switched into the amplifier; this may be adjusted to start at a preselected signal level, depending on operational requirements.

When the fish echo signal is received it is amplified in the normal way, and assuming that the white-line level is correctly set the seabed signal will not be able to rise far above the fish signal before the amplifier will be in effect switched off. The short period after the seabed echo rises above fish echo level, but before amplifier cut-off occurs, is when the thin seabed echo appears on the paper record. A white line or space then occurs for a set period before the tail of the seabed echo is recorded.

2.2.6.5 *Seabed locked systems*

All the systems described up to this point are known as transmission-locked. This is because the instant of transmission of the acoustic pulse is used as the time reference. Movement of the vessel with respect to the seabed is shown as a change of range on the recorder chart. This movement may be quite rapid and result in a chart which is difficult to interpret. When considering fish echoes close to the seabed, for example within a distance of approximately 4 m from it, the normal recorder has a chart width of perhaps only 2 or 3 mm for this distance.

If the fish concentration is dense the white-line circuits will show it clear of the seabed, but it may be that the fish are large ones spaced some distance apart, as often occurs with demersal fish, in which case they could be detected but lost in the "noise" recorded on the chart, due to loss of full trace-to-trace correlation because of ship movement.

For the detection of such fish concentrations, a system is required which will use the seabed as a reference. The problem is that the required fish echoes occur in time before the seabed signal for any given transmission period; that is, the time between one transmission and the next. This means that the fish echoes occurring, for example, in the catching range of a trawl must be delayed in time, so that they occur in the processing circuit after the front edge of the seabed echo. It is beyond the scope of

this section to describe such a system in detail, for the electronic circuits are complex, but recording and cathode-ray tube displays are manufactured with the seabed lock facility. In both cases the seabed signal appears as a straight line at a fixed point on the display. Fish echoes up to about 8 m above the seabed are shown, often as individuals. The delay system can be a magnetic tape record which stores the signals for a given period. It also has the advantage that signals can be repeated many times so that, in the case of the cathode-ray tubes, instead of seeing the signals flash on once per second, a continuous picture is presented. Under favourable conditions the individual fish traces can be counted from the paper record.

2.3 Horizontal echo-ranging systems

Transmission frequencies used in this type of equipment range from 10 to around 200 kHz, the lower frequencies being used for long-range detection because they suffer less attenuation in the sea. At the high frequencies range is short, but narrow beams for small transducers are possible and short pulses give good range resolution.

Most of the features of vertical echo sounders described in the preceding paragraphs apply equally well to the widely used, horizontal echo-ranging equipment. In fact, if the transducer of a vertical echo sounder is turned 90° so that its acoustic pulses travel horizontally it could be termed a horizontal-ranging sonar. However, as shown by the block diagram in Figure 2.10, this type of sonar equipment usually differs from echo sounders in the following ways:

It is possible to lower the transducer below the ship's keel, rotate it in azimuth (bearing control) and tilt it downward.

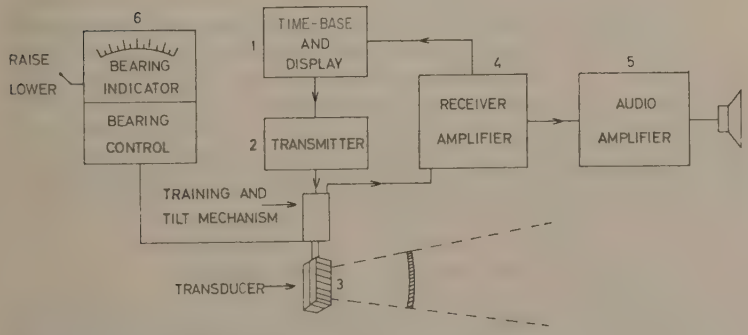


FIGURE 2.10 - Block diagram of horizontal echo-ranging sonar.

There is an additional transducer control unit and bearing display.

Transmitter power and pulse length are greater.

The receiver-amplifier has an additional feature of automatic gain control.

An audio output is provided (block 5).

2.3.1 Time-base and recording display

To be of practical use in fisheries, the sonar must be capable of detecting schools of fish of a reasonable size at its maximum range. At a range of 1 500 m, it takes the sound pulse two seconds to travel from the ship, strike target and be reflected back. This means that the stylus travelling from zero to 1 500 m on the recorder paper will take two seconds. If one stylus pen were being used on a recorder with a circular sweep, approximately three quarters of the total 360° rotation of the pen would be wasted, because during the time that the pen is off the paper the equipment is inoperative. It would also mean that the time between successive transmissions would be about eight seconds.

To avoid this wasted time, a number of pens are used so that as one leaves the paper at the maximum range another is passing zero. The number of transmissions and the sweep speed of the recorder can then be optimized. It is most unlikely that a secondary echo would be obtained from a fish school, so that the reasons given for not using optimum transmission and sweep rates on the echo sounder are therefore not valid for this type of equipment.

2.3.2 Reverberation controlled gain

TVG and initial suppression have been described as forms of automatic gain control for echo sounders. TVG is normally used in sonars over the first 100 m or so of range. However, a more elaborate control of overall gain is needed to prevent volume reverberation from obscuring fish echoes. This is realized by averaging all the signals to produce a DC control voltage. By applying this voltage to a suitable circuit, the amount of control and the time that it is effective can be set. When this circuit is correctly set, fish echoes are not reduced in size immediately they appear and the gain stays constant until the echo ceases.

2.3.3 Control and indication of transducer position

Large volumes of sea can be searched by horizontal echo-ranging sonar by rotating the transducer from side to side, in steps or continuously,

as the ship steams ahead. The speed at which the transducer rotates is determined primarily by the longest range to be searched, since time must be allowed for the sound pulse to travel from the transducer to the target and back again. In the case of the 1 500-m range quoted previously it is two seconds. The transducer should not rotate through more than half its beam-width in this time, or some signals may be lost. The operator is able to "home" on to a school once it has been detected by means of the manual control. Manual training of the transducer by the operator rotating it from one side of the vessel to the other continuously would be very tedious, and for this reason most echo-ranging sonars have an automatic system of training, which can be left unattended. The transducer can be left to train from the extreme bearing on the port side of the ship round to the extreme starboard bearing, or over some desired sector, in which case markers are placed on the azimuth bearing scale so that the desired sector is contained between them. Switches at the marker positions stop and reverse the training motor and this procedure can continue indefinitely.

The bearing scale is usually $\pm$ 150° relative to the ship's head. A number of systems are used to convey the bearing information from the transducer to the bearing indicator, using electrical cable only. Synchronous links, or synchros as they are generally called, provide accurate remote indication of shaft position or bearing.

In many types of sonar equipment it is possible to tilt the transducer downward, in some cases to 90° from the horizontal. This is useful when schools of fish are in close range of the ship and eventually pass underneath it. If a sonar has no tilt control it is usual to fit the transducer at an angle to its shaft so that the beam is tilted downward about 5°. This prevents reflections from the sea surface giving signals.

With a transducer system having no tilt it is often found that a switch is provided to change the vertical section of the beam.

A typical horizontal echo-ranging sonar working at 30 kHz might have a beam-width of 10° $\times$ 10° with a switch to change the vertical part of the beam to 20°, so that a greater volume of sea can be searched. The active face of such a transducer would measure 25 $\times$ 25 cm.

2.3.4 Hull unit

This consists of the lifting, training and tilt mechanisms, in addition to the transducer and dome. Because the sonar transducer has to "look" horizontally under the ship it is mounted on a shaft which, when lowered, projects by about 0.5 to 0.75 m. Around the transducer is a streamlined cover, called a sonar dome. This can be free-flooding or have fresh water sealed inside. Materials used for this purpose must not reflect or absorb too much sound. Those most commonly used are stainless steel, rubber, or fibreglass. At low frequencies steel of about 0.3-mm thickness does not reduce the sound very much. The purpose of the dome is to prevent

noise being generated on the face of the transducer when the ship is steaming.

Usually the small transducers are fitted inside spherical or cylindrical domes which are attached to the transducer shaft. Large transducers may have partly elliptical domes with separate lifting and lowering mechanism.

2.3.5 Transmitter

The system shown in Figure 2.4 also applies to the horizontal sonar, but in addition a second power amplifier is fitted between that shown and the transducer. In this way, peak pulse powers between 1.5 and 10 kW are produced. Pulse lengths of 10 to 30 milliseconds are used when listening for signals on the loudspeaker or earphones but shorter pulses of 0.5 to 3 milliseconds are common when the recorder or plan position indicator (PPI) displays are used alone.

2.3.6 Audio output

The long pulses mentioned in 2.3.5 enable the sonar operator to receive an echo as an audible tone or "ping" instead of a slight click or knock as from short pulses. This is particularly useful where the operator cannot watch the display continuously. The audio signal draws his attention to the fact that a sonar contact has been made.

It is necessary to mix the received pulse with a signal near to its frequency; for example, assuming the received pulse is at 50 kHz and is mixed with a signal of 49 kHz, the difference frequency is 1 kHz, which is audible.

2.3.7 Plan position indicator (PPI)

In the cathode-ray tube systems described above for the echo sounder, the spot of light travels in a straight line across the tube face, and signals cause sideways deflection of the spot. As shown diagrammatically in Figure 2.11, the PPI for the horizontal echo-ranging equipment is quite different in appearance, for although the spot still travels in a line to provide the time-base, this line moves through a sector on the tube in synchronization with the transducer beam.

Thus the bearing of a fish echo may be shown in relation to the ship's head. In this system the echo signal causes an increase in intensity of the electron beam and brightens this point on the time-base line. The persistence of the tube phosphor is several seconds, so that echoes may be correlated from trace to trace.

The echo signals shown on the PPI display in Figure 2.11 are only typical for a short-range high-frequency sonar where the transducer can be turned

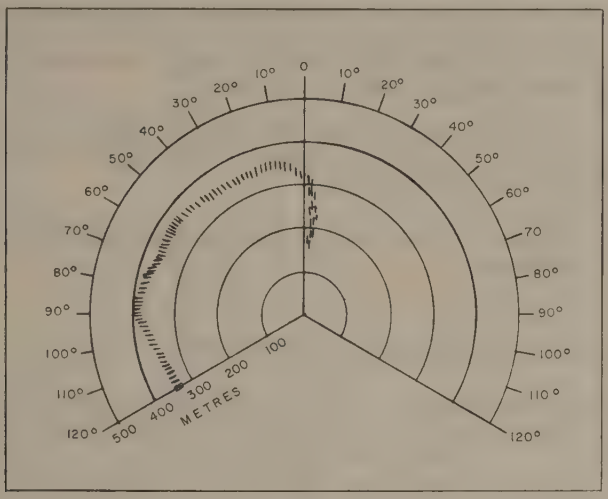


FIGURE 2.11 - Diagram of PPI display, showing echo starting at 350 m range on 120° bearing and ending on 150 m range and 3° bearing.

around quickly. In the example the trace could be from a ribbon-like school of fish. A PPI display is obtained either by varying the voltages in a special way on the deflector plates of a CRT similar to that described in 2.2.3, or more generally by the use of a different type of CRT. This is known as an electromagnetic tube. The electron beam is formed and focused in the same way, but is deflected by the magnetic field from coils fitted externally. By turning the coils in synchronization with the transducer beam, the time-base line will follow and indicate the bearing.

2.4 Factors affecting the choice of equipment

In fitting out a ship with acoustic equipment it is often difficult to decide on the most suitable instrument. Tasks for the ship may differ from cruise to cruise, as may the area in which it works. In choosing a general purpose instrument one can in certain circumstances lose the advantages that a special instrument would have given.

A wide range of frequencies are now available in acoustic equipment for the detection of fish. These range from 10 to 300 kHz. Briefly, the effect of frequency can be summarized as below:

The *lower* the frequency the *longer* the range for a given set of operating conditions, because attenuation is low. Range resolution will be poor as the minimum pulse will be relatively long. Transducers are large, if reasonably narrow beams are required.

When *high* frequencies are used the detection range becomes short, but good range resolution is possible. However, narrow beams can be obtained with small transducers.

Table 2.1 gives a rough guide to equipment selection, but is by no means comprehensive.

2.5 Calibration of echo sounder and sonar systems

The voltage amplitude of a reflected signal, appearing at the receiver output terminals of an echo-ranging system, will depend on the reflecting properties of the target, but also to a large extent on the receiving sensitivity and transmitting power. When these two system parameters are known one should be able to judge the target properties from the amplitude characteristics of the received echo signal.

To calibrate hydroacoustic equipment involves obtaining the measurements of the parameters of the transmitting/receiving system.

To calibrate the receiving system involves establishing the relation between the signal deflection on an oscilloscope connected to the receiver output terminal and the sound pressure in front of the receiving transducer causing this deflection.

To calibrate the transmitting system involves establishing the relation between the power setting on the transmitter and the corresponding sound pressure in water.

2.5.1 Reasons for calibration

There are three major reasons why the calibration of hydroacoustic instruments is necessary:

To check that the complete system is working properly according to its specification. This should include the following measurements:

transmitting sound pressure (source level)
receiving voltage response
receiving linearity, band-width
transducer impedance
transducer directivity
transmitting power, pulse-width, beam-width, frequency, etc.

TABLE 2.1. — GUIDE TO SELECTION OF ACOUSTIC EQUIPMENT

Equipment	Frequency band	Display unit	Purpose
SONAR	1	Paper recorder	Long-range school detection,[1] middle-range school detection
	2	Paper recorder and sonar scope	Middle-range school detection,[1] purse seining
	3	Sonar scope	Short-range school detection, purse seining [1]
ECHO SOUNDERS			
With white-line	1	Paper recorder (moist)	Fish-finding in very deep water, depth sounding
Without white-line	2	Paper recorder (dry)	Navigation,[1] purse seining
With white-line and TVG	2	Paper recorder (moist)	Pelagic [1] and demersal trawling, purse seining
	2	Paper recorder (moist) and scope	Demersal trawling in deep waters, fish-finding in deep and shallow waters
Seabed locked with white-line	2	Paper recorder (moist) and paper recorder (dry) expanded scale scope expanded scale	Demersal trawling in deep waters,[1] fish-finding [1]
With white-line and TVG	3	Paper recorder (moist)	Pelagic and demersal trawling, purse seining, towed bodies
	3	Paper recorder (moist) and scope	Demersal trawling in deep and shallow waters, fish-finding
	4	Paper recorder (dry) or recorder with expanded scale and moist paper	Demersal trawling in shallow waters,[1] and for all purposes in very shallow waters [1]

NOTE: 1 = 10 - 25 kHz (very deep waters, 500 m and more)
2 = 30 - 50 " (deep waters, 150 - 500 m)
3 = 80 - 120 " (shallow waters, 50 - 150 m)
4 = 150 - 300 " (very shallow waters, 50 m and less)

[1] Equipment recommended especially for this purpose.

To measure the absolute value of noise level, which is one of the limiting factors in the use of hydroacoustic instruments.

To use the hydroacoustic instruments to measure the received echo level, and thus determine the back-scattering strength of the reflecting object.

2.5.2 Ambient conditions during calibration

Calibration should be carried out with the vessel at anchor. The depth, particularly when a depth sounder is to be calibrated, should be a minimum of 5 to 6 m below the keel of the vessel. Avoid nearby underwater obstructions which may cause reflections and thereby affect calibration results. It is also important to choose a site with a minimum of ambient noise from, for instance, shipyards or passing vessels. Calibration should not be carried out in high ambient noise level or in turbulent water conditions.

2.5.3 Calibration instruments

The reliability of the calibration will depend to a great extent on the instruments used; high-quality instruments are preferred. In many cases it will be convenient to use instruments powered by rechargeable nickel cadmium cells. Even if the instruments are of high quality they should be periodically checked against laboratory standards. The following instruments are needed:

Calibrated test transducer or hydrophone. It is important to obtain the calibration for both reception and transmission. It should be noted that calibration can be badly affected by use at other than the temperature at which calibration was certified.

Oscilloscope with calibrated time and amplitude scales.

A signal generator, preferably having both pulse and continuous wave output. This must cover the frequency of the echo sounder or sonar system under test. It should have a calibrated output voltage or an attenuator calibrated in dB relative to 1 volt at a known impedance.

Frequency counter.

Amplifier voltmeter.

In this connexion it may be useful to discuss a typical low-frequency test hydrophone, for example the LC 32. This hydrophone, which is a reversible transducer, has a 4-cm ceramic cylinder as the active element.

The directivity pattern is approximately circular in the horizontal plane up to 100 kHz. At a frequency of 120 kHz one should expect deviations of 2 to 3 dB from a circular pattern. In the vertical plane the directivity is as for a 4-cm line antenna; that is, at 50 kHz the beam-width in the vertical plane is approximately 50° and at 100 kHz approximately 25°.

The receiving voltage response is reasonably flat up to 20 kHz. Above 20 kHz the response varies somewhat, to some extent dependent on temperature.

The receiving voltage response S_{Rt} for a test hydrophone is expressed in:

dB//1 volt per μBar

The receiving voltage response at 20 kHz for the LC 32 unit is approximately:

—103 dB//1 volt per μBar

Recommended cable length for a test hydrophone is about 15 metres. In many cases this length will be insufficient and an extension cable is required. An extension cable, however, will increase the hydrophone load, thereby reducing its receiving voltage response. Nine metres of extension cable reduces the receiving voltage response by approximately 0.5 dB.

The transmitting voltage response of the LC 32 unit increases 12 dB per octave of frequency up to resonance, which occurs at approximately 60 kHz. For higher frequencies the response is quite irregular. In the transmitting mode the applied voltage to the test hydrophone should not exceed 10 volts rms.

The transmitting voltage response S_{tt} for a test hydrophone is expressed in:

dB//1 μBar per volt at 1 m distance

The transmitting voltage response at 20 kHz for the LC 32 hydrophone is approximately:

25 dB//1 μBar per volt at 1 m distance

An exact knowledge of the test hydrophone performance is important if an accurate calibration is desired. Therefore the test hydrophone should be calibrated regularly.

2.5.4 Procedure

2.5.4.1 *Alignment of the test hydrophone*

If a sonar is to be calibrated, the positioning of the hydrophone is quite simple. The hydrophone is lowered into the water until it is level with the transducer (Figure 2.12). The horizontal distance between the hydrophone and the transducer should be between 3 and 7 m. Shorter distances than 3 m should be avoided, particularly when dealing with large transducers.

A signal generator tuned to the centre frequency of the receiving system is connected to the test hydrophone.

It is difficult to calibrate receiving systems using a paper recorder as the output indicator. Minimum Recordable Signal on the paper is a useful reference but is not precise enough to be used as a basis for calibration.

This difficulty is overcome by connecting either an oscilloscope or high-impedance voltmeter to the receiver output across the video output jack or terminals of the recording stylus. A load resistance is also fitted in place of the paper; the value is not very critical, being typically 2 to 5 kilo-ohms for a moist-paper recorder and 10 to 50 kilo-ohms for a dry-paper type. The same value should always be used for a particular instrument. An output voltage must now be chosen which will be the reference for calibration: this would be between 4 and 10 volts in moist-paper and 70 and 100 volts in dry-paper systems.

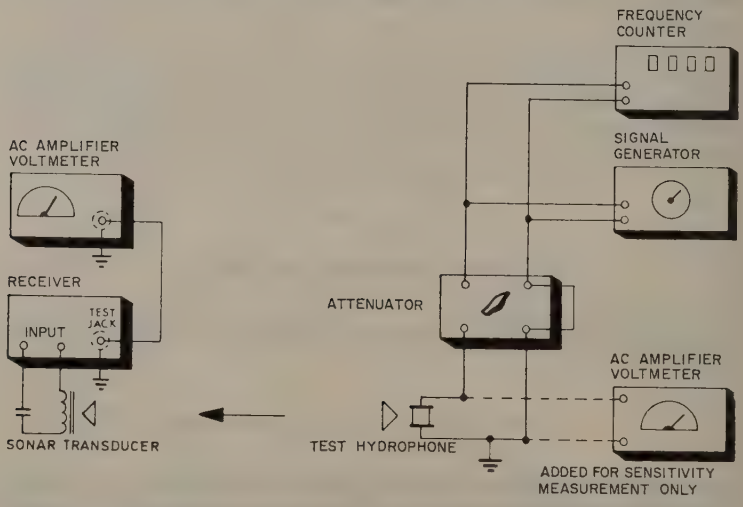


Figure 2.12 - Instrument connexion for alignment of hydrophone and calibration of the receiving system.

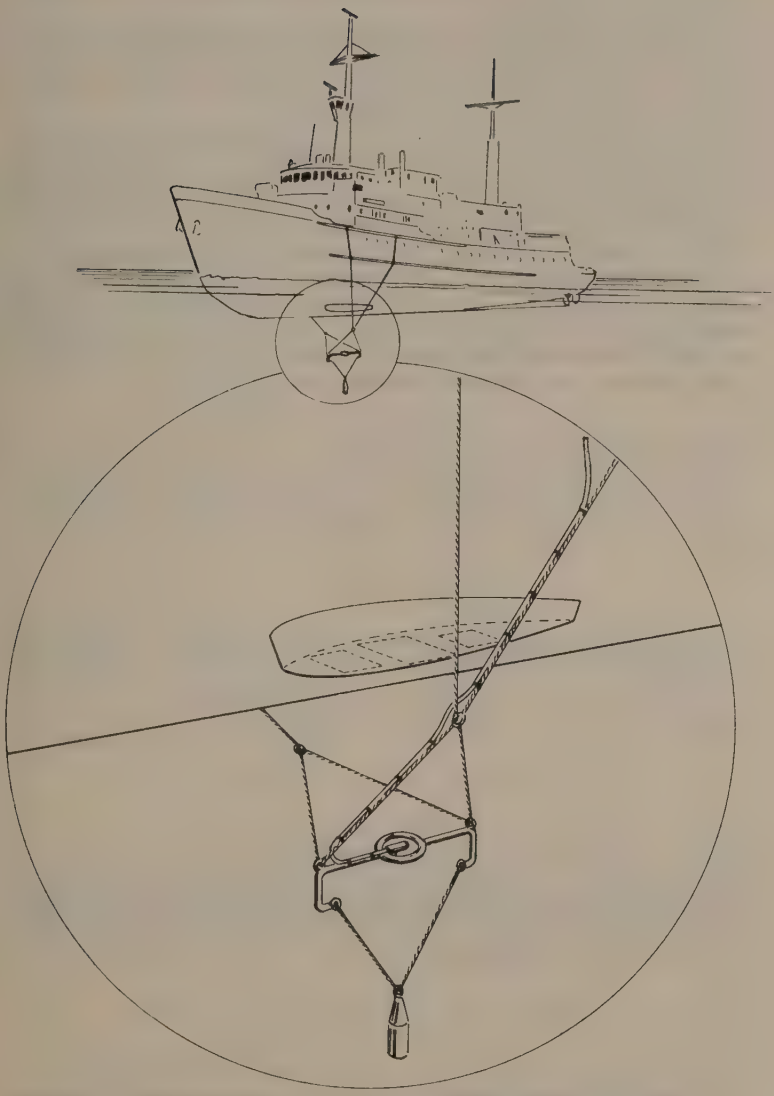


FIGURE 2.13 - Alignment of test hydrophone, echo sounder calibration.

The input signal level to the hydrophone is adjusted to keep the sonar receiver below saturation.

By training the sonar transducer and lowering and hauling the test hydrophone one soon finds the acoustic axis where the voltmeter shows a maximum. Make sure that it is the main lobe of the transducer's radiation pattern which is directed at the hydrophone.

When calibrating an echo sounder the hydrophone alignment is not quite as simple as for sonar. A rig carrying the test hydrophone is suspended, as shown in Figure 2.13. The positioning of the test rig can be tedious; however, if the location of the transducer is well established it should not be too difficult to find the acoustic axis.

Final adjustment of hydrophone positioning is obtained by connecting the test hydrophone to the vertical amplifier input of an oscilloscope, while the transmitter is operating on the shortest pulse length and the fastest triggering rate (see Figure 2.14). The test hydrophone is now adjusted for maximum signal deflection on the oscilloscope. This method is recommended for both sonar and echo-sounder calibration.

2.5.4.2 *Measuring the source level (SL)*

With the test hydrophone lined up, the source level may now be measured. Source level is usually expressed in:

$$\text{dB//1 } \mu\text{Bar ref 1 m}$$

If the peak-to-peak voltage across the test hydrophone in Figure 2.14 is 6 volts:

$$V_{hydr} = 6 \text{ volt}_{p\text{-}p}$$

$$V_{hydr} = \frac{6}{2\sqrt{2}} = 2.12 \text{ volt}_{rms}$$

$$V_{hydr} = 20 \log 2.12 = 6.5 \text{ dB//1 volt}$$

If the receiving voltage response S_{Rt} for the test hydrophone is —103.5 dB//1 volt per μBar at the operating frequency of the equipment, the sound pressure at the test hydrophone is:

$$P_{hydr} = V_{hydr} - S_{Rt}$$

$$P_{hydr} = 6.5 - (-103.5) = 110 \text{ dB//1 } \mu\text{Bar}$$

However, the sound pressure 1 m in front of the transmitting transducer is needed. This is expressed as:

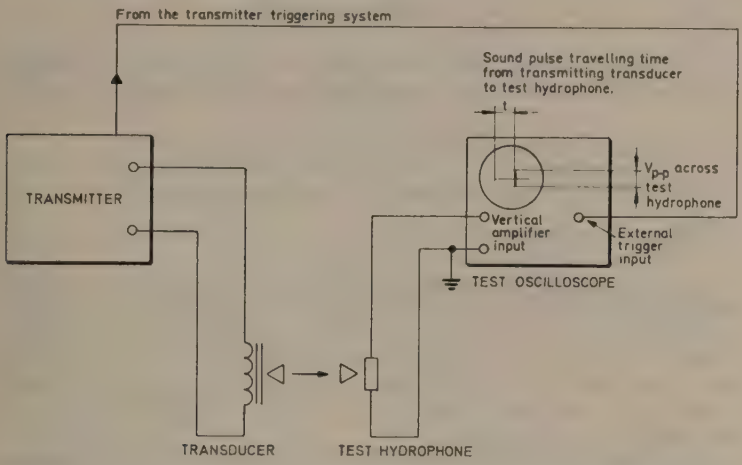


FIGURE 2.14 - Instrument connexion for determination of sound pulse propagation time from transmitting transducer to test hydrophone and for source level measurement.

$$S = V_{hydr} - S_{Rt} + 20 \log R$$

where R is the distance in metres between the transducer and the test hydrophone. As the spreading of sound follows an inverse square law, the sound pressure at a distance of 1 m in front of the transducer is 20 log R higher than the pressure at the test hydrophone. The distance R is calculated from the formula

$$R = c.t$$

where c is the velocity of sound in sea water and t is the pulse propagation time between the transducer and the test hydrophone. With the arrangement shown in Figure 2.14, t may be measured along the horizontal axis of the test oscilloscope.

If t is found to measure 3 msec and assuming c to be 1500 msec:

$$R = 1500 \times 3 \times 10^{-3} = 4.5 \text{ m}$$

The source level is:

$$SL = 110 + 20 \log 4.5$$

$SL = 110 + 13 = 123$ *dB//1 μBar ref 1 m*

The source level measurement should now be repeated for the different power settings, beam-widths, pulse lengths and pulse repetition rates.

2.5.4.3 *Measuring the receiving voltage response* (V_R)

The receiving voltage response is usually expressed in:

dB//1 volt per μBar

The arrangement for measurement of the receiving voltage response is shown in Figure 2.12. This is also useful for a check of the band-width, the linearity and the saturation level of the receiver, as well as ambient noise level. If the saturation level of the receiver appears to be 3 to 5 volts rms, adjust and record the hydrophone input voltage V_{hydr} to obtain a reading of 1 volt rms (0 dB) on the amplifier voltmeter connected to the receiver output terminals.

The transmitting response of the test hydrophone on the operating frequency is read off the hydrophone calibration curves:

S_{tt} = 30 dB//1 μBar per volt ref 1 m

and the measured voltage across the test hydrophone is:

V_{hydr} = 0.056 volt rms

i.e., $V_{hydr} = 20 \log 0.056 = -25$ dB//1 volt

The sound pressure level 1 m from the hydrophone is:

$S_{tt} + V_{hydr}$

i.e., $30 - 25 = 5$ dB//1 μBar

The pressure level L at the receiving transducer is wanted.

$L = S_{tt} + V_{hydr} - 20 \log R$

If the hydrophone alignment is the same as for the source level measurement:

$L = 30 - 25 - 13 = -8$ dB//1 μBar

The receiving voltage response V_R for a calibrated receiving system is:

$V_R = V_r - G - L$

or

$V_R = V_r - G - (S_{tt} + V_{hydr} - 20 \log R)$

V_r = output voltage from receiver (dB//1 volt)

G = calibrated gain control setting (dB)

S_{tt} = transmitting voltage response of test hydrophone (dB//1 μBar per volt ref 1 m)

V_{hydr} = voltage across test hydrophone necessary for a voltage of 1 volt (0 dB) at the receiver output

R = distance in metres between the transducer and the test hydrophone.

2.5.5 Calibration accuracy

The overall accuracy of the calibration is dependent on:

hydrophone alignment
accuracy of test hydrophone
accuracy of amplifier voltmeter
accuracy of oscilloscope

The accuracy of the electronic instruments used can easily be kept within ± 0.2 dB. The expected accuracy of the calibration of the hydrophone is ± 0.5 dB. If one is very careful when carrying out the calibration, therefore, it is possible to obtain results with overall accuracy better than ± 0.7 dB.

2.6 Exercises (based on Sections 1 and 2)

(Note: In the following examples the sound velocity in the sea is assumed to be 1 470 metres per second.)

Example 1 What is the wavelength in centimetres corresponding to a sound frequency of 30 kHz?

Answer

$$\lambda = \frac{c}{f}$$

where c = velocity = 1 470 m/sec = $1\,470 \times 10^2$ cm/sec

f = frequency = 30 kHz = 3×10^3 Hz

$$\lambda = \text{wavelength in cm}$$

$$= \frac{1\,470 \times 10^2}{30 \times 10^3} \text{ cm}$$

$$= 4.90 \text{ cm}$$

Example 2 Calculate the length in metres of the sound pulse in the sea corresponding to a pulse length of 3 milliseconds.

Answer Length of pulse in sea $= c \cdot \tau$

where c = velocity = 1 470 m/sec

τ = pulse length = 3 milliseconds

$c \cdot \tau = 1\,470 \times 3 \times 10^{-3}$ m

$= 4.410$ m

Example 3 Calculate the number of cycles in a pulse of 1 millisecond at 30 kHz.

Answer 30 kHz $= 30 \times 10^3$ cycles per second

$= 30 \times 10^3 \times 10^{-3}$ cycles per millisecond

= 30 cycles per millisecond

= 30 cycles in 1 millisecond pulse

Example 4 What is the depth of bottom if the bottom echo is received 0.5 second after transmission?

Answer $\text{Depth} = \frac{c \cdot T}{2}$

where c = velocity = 1 470 m/sec

T = time sound takes to travel to bottom and return, in seconds

$$\text{Depth} = \frac{1\,470 \times 0.5}{2} \text{ m}$$

$$= 367.5 \text{ m}$$

Example 5 The cross-sectional area insonified at a depth of 10 metres by the beam of a particular echo sounder is 2 square metres. What area will be insonified at 50 metres range?

Answer

$$A_2 = A_1 \times \left(\frac{d_2}{d_1}\right)^2$$

i.e., cross-sectional area increases as distance^2

where A_1 = area at 10 m = 2 m^2

d_1 = distance 1 = 10 m

d_2 = distance 2 = 50 m

A_2 = area 2

$$= 2 \left(\frac{50}{10}\right)^2 \text{ m}^2$$

$$= 2 \times 25 \text{ m}^2$$

$$= 50 \text{ m}^2$$

Example 6 Given a sound source with a source level of 100 dB//1 μBar, what is the sound level on the acoustic axis at a depth of 100 metres? Attenuation coefficient $\alpha = 0.01$ dB/metre corresponding to frequency of 38 kHz.

Answer

$$L_{(R,\theta,\varphi)} = SL + 10 \log b_{(\theta,\varphi)} - 20 \log R - \alpha R$$

$$L_{(R,0,0)} = SL + 0 - 20 \log R - \alpha R$$

where SL = source level = 100 dB//1 μBar

R = depth in m = 100

α = 0.01 dB/m

$L_{(R)} = 100 + 0 - 20 \log 100 - 100 \times 0.01$

$= 100 - 20 \times 2 - 1$ dB//1 μBar

$= 100 - 40 - 1$ dB//1 μBar

$= 59$ dB//1 μBar

Example 7 The intensity of sound at 100 metres is only 1/10 000 of the intensity at 1 metre from a transducer as a result of geometric spreading.

(*a*) What is the intensity difference in decibels?

(*b*) What is the corresponding relationship between sound pressures at these distances?

Answer (*a*) Sound level $L = 10 \log \frac{I_R}{I_o}$

where I_o = intensity at 1 m

I_R = intensity at 100 m

$$L = 10 \log \frac{I_o \times 10^{-4}}{I_o} \text{ dB}$$

$$= -10 \times 4 \text{ dB}$$

$$= -40 \text{ dB}$$

(*b*) Sound level $L = 20 \log \frac{p_R}{p_o}$

where p_R = pressure level at 100 m

p_o = pressure level at 1 m

But $L = 20 \log \frac{p_R}{p_o} = 10 \log \frac{I_R}{I_o}$

$$= 10 \log 10^{-4}$$

$$\left(\frac{p_R}{p_o}\right)^2 = 10^{-4}$$

$$\frac{p_R}{p_o} = 10^{-2}$$

$$= 1/100$$

Sound pressure at 100 m is 1/100 of sound pressure at 1 m

Example 8 Given: source level $SL = 120$ dB//1 μBar, frequency 120 kHz with attenuation coefficient $\alpha = 0.04$ dB/metre. What would the echo level from a target at 100 metres be with a target strength of —30 dB?

Answer

$$EL = SL - 2(20 \log R + \alpha R) + TS \text{ dB//1 μBar}$$

$$= 120 - 40 \log R - 2\alpha R + (-30) \text{ dB//1 μBar}$$

$$= 120 - 40 \log 100 - 200 \times 0.04 - 30 \text{ dB//1 μBar}$$

$$= 120 - 40 \times 2 - 8 - 30 \text{ dB//1 μBar}$$

$$= 120 - 80 - 8 - 30 \text{ dB//1 μBar}$$

$$= 2 \text{ dB//1 μBar}$$

Example 9 Given: source level = 130 dB//1 μBar, frequency 38 kHz with attenuation coefficient $\alpha = 0.01$ dB/metre. What is the target strength of a target at 200 metres which gives an echo level of 10 dB//1 μBar?

Answer

$$EL = SL - 2(20 \log R + \alpha R) + TS$$

$$TS = EL - SL + 40 \log R + 2\alpha R \text{ dB//1 μBar}$$

$$= 10 - 130 + 40 \log 200 + 400 \times 0.01 \text{ dB//1 μBar}$$

$$= 10 - 130 + 40 \times 2.3013 + 4 \text{ dB//1 μBar}$$

$$= 10 - 130 + 92.052 + 4 \text{ dB//1 μBar}$$

$$= -23.95 \text{ dB//1 μBar}$$

Example 10 Given: frequency of 38 kHz with an attenuation coefficient $\alpha = 0.01$ dB/m. What minimum source level would be needed to detect targets with target strengths of —30 dB down to a depth of 300 metres when the minimum measurable echo level is —30 dB//1 μBar?

Answer

$$SL = EL + 40 \log R + 2\alpha R - TS \text{ dB//1 μBar}$$

$$= -30 + 40 \log 300 + 2 \times 300 \times 0.01 - TS \text{ dB//1 μBar}$$

$$= -30 + 40 \times 2.4771 + 6 - (-30) \text{ dB//1 μBar}$$

$$= -30 + 99.084 + 6 + 30 \text{ dB//1 μBar}$$

$$= 105.084 \text{ dB//1 μBar}$$

Minimum source level = 105.1 dB//1 μBar

SECTION 3. THE IDENTIFICATION OF TARGETS AND CHARACTERISTICS OF ECHO RECORDS

3.1 General

The problem of identifying the echoes obtained from a particular species (or group of species) of fish is clearly of major importance in determining the accuracy with which echo survey can be applied in studying them quantitatively.

There are no general rules which will allow a species of fish to be identified directly from its echo trace. This is because there is no species of fish so consistent in its behaviour as to give at all times the same echo pattern, and because different species of fish exhibit similar patterns of distributional behaviour and so give rise to similar echo records. Therefore, the kind of information that can be extracted with certainty from such records can usually only be exemplified by such statements as:

This trace definitely represents a dense pelagic school not more than 30 m across.

This trace definitely represents a large dense pelagic school at least 300 m in extent.

This trace represents either a pelagic distribution of large single fish or a pelagic distribution of small fish schools not more than 10 m each in extent and not more than 2 m in vertical extent.

This diffuse trace represents either a dense layer of planktonic organisms, or a layer of fish widely dispersed.

It is true that in some instances the element of doubt about the species giving rise to particular types of echo record in a survey area is negligibly small, as in the case of some pelagic schooling species, such as a herring population which at the time is being actually exploited by, say, a purse seine fishery, and is shown to be the only pelagic schooling species in the area in question. In such a situation the "plume-shaped" traces characteristic of a fish school can be treated with confidence as being herring. However, in many situations where a number of species of fish occur together and have a similar distributional behaviour, doubts about the identity of the echo records will only be dispelled after the application of

several methods which give supporting evidence. There will also be examples in which different methods suggest different answers, and so it may not be possible to reach definitive conclusions.

3.2 Methods of identification

3.2.1 Catch sampling

One obvious method of identification used in association with echo survey is to sample the fish (or other organisms) giving rise to the echo traces with appropriate catching gear. These methods are widely employed, use being made either of special sampling gear from research vessels or, if appropriate, of the catches taken by a fishery in the survey area. The accuracy of such methods is, of course, governed by the selective properties of the sampling gear, as exemplified by a large mesh trawl. Efforts must be made to reduce such selectivity to a minimum, such as in trawl sampling by the use of small mesh covers on the cod-end. Even so, it must be recognized that selection by factors other than cod-end mesh size may be so severe as to invalidate the study. It is therefore of major importance that the choice of sampling method should be considered critically for each type of echo survey situation and, if necessary, a combination of sampling gears, relevant for different types of fish or other organisms, should be used. Also, wherever possible, other independent direct methods of sampling or identification should be employed as well as the catching gear.

3.2.2 Other methods of identification

Among other methods of sampling or identification are the following: the use of explosive charges; the use of underwater photography; direct observation by divers or men in underwater vehicles; television. To these might be added two methods which have not yet been reported, but seem to offer some useful features: small-scale electrical fishing, and investigation of stomach content of birds and predatory fishes.

Use of explosives. Many species of fish, if killed or stunned by explosives, will rise to the surface and float for a while. These can be collected for identification by a small hand-operated net used from the ship or a small boat. One successful method of operation is to mark the position of the echo trace with a suitable float and detonate a small towed charge electrically. A merit of the use of explosives is that it is a very quick operation compared to any commercial fishing method, and is highly specific as to position. A 100-g charge will stun fish up to a distance of

4 or 5 m and so the resultant catch can be fairly definitely associated with the echo-sounder recording. Small charges such as this are effective in dealing with schools of fish down to about 20 m depth. In deeper water, large charges, perhaps of 50 kg or more, are necessary. Explosives are scarcely to be recommended unless the staff concerned are familiar with them.

Photography. Cameras suspended in the sea, or attached to fishing gear, offer a means of adding information to direct catch sampling.

Suspended cameras are only rarely useful, since avoidance reactions may occur and it is difficult to ensure coincidence of camera and the targets giving rise to the echoes. (The camera can usually be seen on the echo sounder, but coincidence of its echo trace with the fish trace only confirms equality of range.) However, with dense and relatively inactive fish concentrations, apparently typical of fish in cold water, useful identifications have been reported by the use of suspended cameras.

Cameras attached to fishing gear, particularly to the demersal trawl, are very effective in checking the fish population traversed and herded by the net. It is not uncommon with this method to obtain evidence of the presence in the vicinity of the fishing gear of species, which by virtue of their activity or small size, are not represented in the catch.

Direct observations. Divers using scuba equipment can be extremely efficient observers where light is adequate and visibility good. There are severe limitations on operational depth: for instance, it seems surprisingly difficult for a diver to contact schools of active fish such as herring. There are also fairly severe limitations on open sea working in any but the best of weather.

Some of these limitations will be overcome by submersible vehicles — self-propelled or towed from the parent ship. Submersibles are not yet commonly enough available to suggest this as a normal identification method.

Television. This method is superficially attractive, but its chief advantage over the camera is the much larger observing time available. Against this, its relative frailty and clumsiness usually make it a less appropriate choice. If it should prove possible to miniaturize television cameras of high sensitivity at low light values, the balance of advantage may be shifted in their favour.

It is evident that present difficulties in the reliable identification of targets giving rise to echo traces may be substantial, and must be considered carefully for each situation in which echo-survey methods are to be applied, especially in abundance studies. Work currently in progress on the acoustic properties of fish, especially on their swim-bladder resonance, may provide a direct method of identifying fish species acoustically. The patterns of sounds produced by some species of fish may also prove useful for this

purpose. However, for the present, use must be made of a combination of the independent methods outlined above.

3.3 Characteristics of echo records

Although there are no general rules for direct acoustic identification, useful information about targets can be obtained by a careful examination of the recording paper. The nature of the echo records is determined not only by the types of target, but also by instrument characteristics and operating conditions, and maximum information from echo records can only be obtained after long personal experience. In this section, however, an attempt is made to explain the basic principles of echo-record interpretation by demonstrating examples of various types of recordings.

3.3.1 Echo sounder records

3.3.1.1 *General characteristics of echo records*

In the ordinary vertical echo sounder, the sound beam can be likened to a searchlight pointing from the transducer in the bottom of the ship toward the seabed, as shown in Figure 3.1. But unlike a continuous searchlight beam, the sound beam is pulsed and the water column is "searched" when the sound pulse is emitted from the transducer. The shape of the beam, the length of the sound pulse and the frequency of the sound are all factors of considerable importance in determining the type of echo record produced. The most important characteristics and controls of an echo sounder are:

frequency (fixed)
beam shape (mainly fixed, but may be variable)
pulse length (variable)
gain (variable)
transmitting power (fixed, but may be variable)
depth range selector, or pulse rate (variable)
paper speed (variable)
white-line effect (fixed or variable)

The influence of these controls and characteristics on the various types of echo records is discussed in later sections, but a few points of general interest are given below.

The shape of the sound beam in many echo sounders is narrower in the fore and aft direction than abeam. A narrower fore and aft beam will give a better horizontal resolution while a wider sound beam will ensure better coverage. The sound beam is not cylindrical but conical, and the sound energy is distributed over a wider area as depth increases,

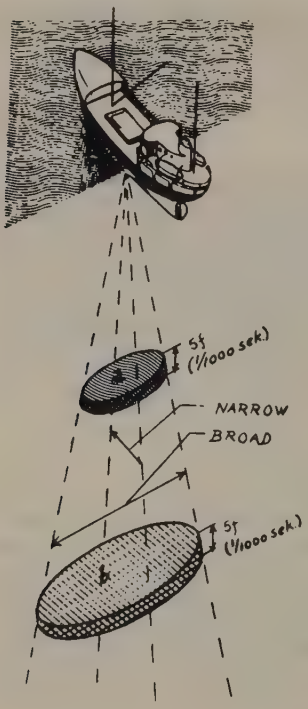


FIGURE 3.1 - Echo sounder pulse and shape of the sound beam.

as shown in Figure 3.1. For example, at a depth of 200 m the area of the sound cone is four times its size at 100 m. This is the main reason (see Section 1) why echoes from targets near the transducer are stronger than from those at greater depths. As shown in Section 2, more advanced instruments have an automatic built-in gain control (TVG) which compensates for the reduction with depth of sound field intensity, so that the effects of distance on echoes from the transducer are eliminated.

One effect of a change of the *speed* at which the recording paper passes through the recorder is to change the relative dimensions of the echo records. The horizontal scale of the echo record depends on paper speed as well as the speed of the vessel. The effect of a change of either of these factors is illustrated in Figure 3.2.

In the upper part of this figure, the topography of the sea bottom is drawn in the same horizontal and vertical scales and the two echo recordings shown below were made with paper speeds of 15 mm/min and 5 mm/min respectively. A similar change would have been produced at constant paper speed by a change of vessel speed from 5 to 15 knots. One should

note that in ordinary paper recorders the horizontal and vertical distances are shown at widely different scales. At normal cruising speed, the vertical scale will be 20 times or more greater than the horizontal, and this will, of course, result in a corresponding distortion of the relative dimensions of, for instance, fish schools which are recorded. Thus, the characteristic traces of fish schools often described as "plumes" and "comets" only exist on echo diagrams, and their shape will depend on the amount of distortion of the horizontal and vertical dimensions which vary accordingly with paper speed, pen speed and the speed of the vessel. These characteristic school shapes, often used for purposes of identification, are thus not always directly comparable between vessels and different kinds of equipment.

3.3.1.2 *Records of seabed echoes*

Besides depth, the echo sounder may give information on a number of characteristics of the seabed itself. The most important are its slope, and whether it is smooth or rough, soft or hard. Figure 3.3 demonstrates several of these characteristics.

On the left of this echo diagram the vessel passed over smooth level ground, which suddenly changed to rough and uneven. It can also be deduced from the recording that the level ground was hard, probably rocky. The difference in width of the two types of trace indicates this.

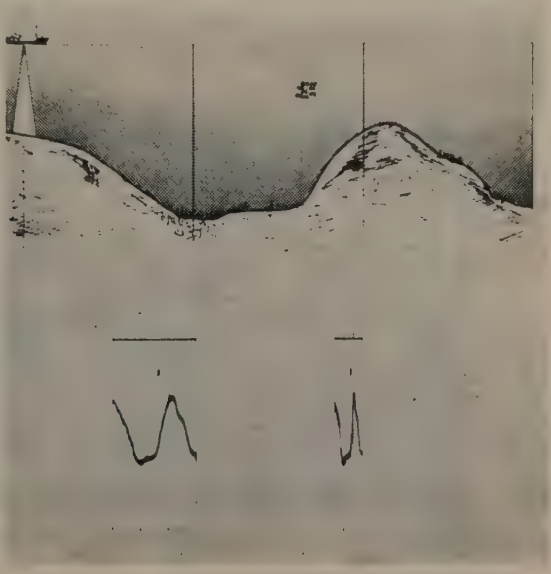


FIGURE 3.2 - Relative dimensions of echo sounder records at different paper speeds.

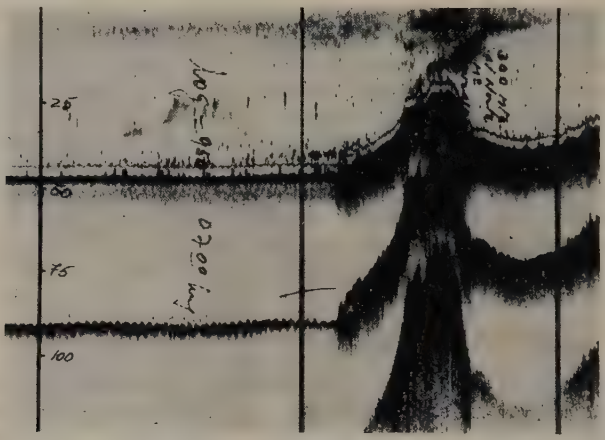


FIGURE 3.3 - Echo sounder record of smooth soft bottom, and uneven hard bottom. (Note also double and triple bottom echoes.)

The soft ground echo was weaker, and therefore produced a narrower trace than the stronger echo reflected from the hard ground. This is due to the differences in their reflectivity, so that the narrower trace comes from an effectively narrower beam. The width of the trace will, of course, also vary with depth and the sensitivity used, but with some experience and training the operator will be able to judge the character of the seabed from the echo record.

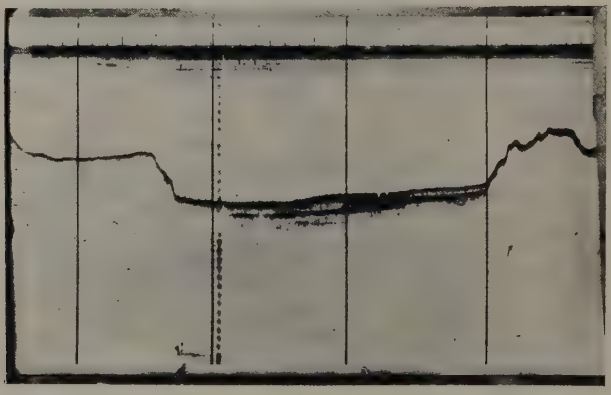


FIGURE 3.4 - Echo sounder record of layers of different kinds of bottom deposits in a Norwegian fjord (from Rollefsen, 1935).

Layers of seabed deposits may be recorded with certain types of echo sounders. Figure 3.4 shows an example from a study where a search for deposits of soft mud was used to locate habitats for deep-water shrimp.

In shallow waters not one but several echoes may be obtained from the seabed. This is because the sound, after having been reflected from the seabed back to the ship, is reflected down again by the sea surface and thus produces a second seabed echo. A whole series of such echoes may be recorded. Figure 3.3 shows a second and a third echo.

Figure 3.5 shows a record of a steeply rising bottom where the depth range was changed to cover the bottom variation. The gradient presented on the echo diagram depends on the speed of the vessel and paper speed. It should be noted that the recorded depth over a steeply sloping bottom will be an underestimate of the true depth, and the gradient measured from the echo record will also tend to differ from the true gradient.

When using a sensitive echo sounder in depths of water beyond the depth scale set on the recorder, the so-called "ghost bottom" may be recorded. This is the true seabed echo being recorded at an incorrect scale. When the seabed is beyond the set scale the pen returns to the zero position before the seabed echo returns, and a new transmission is made before the echo is recorded. Figure 3.6 shows an example of a ghost bottom. In this example the trace disappears at very shallow depths. This is caused by the initial suppression of the echo sounder in the range 0 to 10 or 20 m, and demonstrates that the echoes from the ghost bottom were relatively weak. Another demonstration of the weaker echo from a ghost bottom as compared to that from a true, shallow seabed recording is that the white-line effect will usually not occur in the ghost bottom trace.

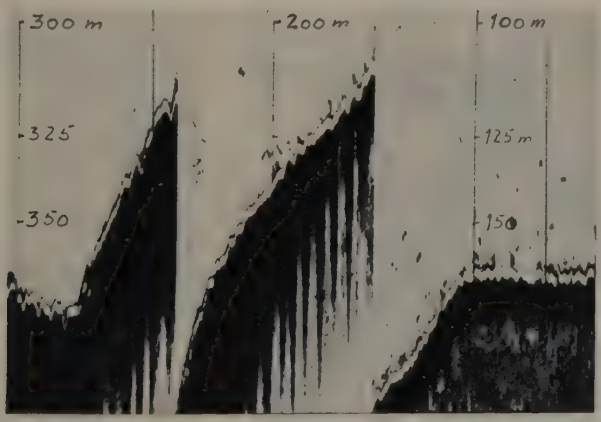


FIGURE 3.5 - Echo sounder record of steeply rising bottom, with shift of depth ranges in order to cover bottom variations.

Ghost bottom recordings have given rise to many reports on new, hitherto unknown, shallow banks and great fish concentrations which have mysteriously disappeared on further investigation. An experienced operator, however, can easily recognize ghost bottom traces.

3.3.1.3 *Records of fish off the seabed*

Single fish records (*resolution*). Fish records may show each individual specimen separately, or the echoes from two or more fish may overlap or join up to form a multiple echo. It is interesting to study the conditions for the separate recording of individual specimens. In the vertical direction, this will be related to the pulse length of the transmitted sound. If the vertical distance between two fish is less than half the pulse length, their echoes will overlap. A simplified diagram illustrating this is shown in Figure 3.7.

The pulse duration in ordinary echo sounders is of the order of 1 or 2 milliseconds. With a duration of 1 millisecond the corresponding length of the sound pulse is 1.5 m. Two milliseconds will give a sound pulse of 3 m. Figure 3.8 shows a fish record where the pulse length was varied from 1 to 3 and finally to 12 milliseconds. The higher power of resolution at the lowest pulse length shown on the left-hand side of this echo record is clearly evident.

In some recent echo sounders designed for research purposes, very short pulse lengths have been used with relatively high transmission frequencies (100-200 kHz) and narrow beams, in attempts to resolve

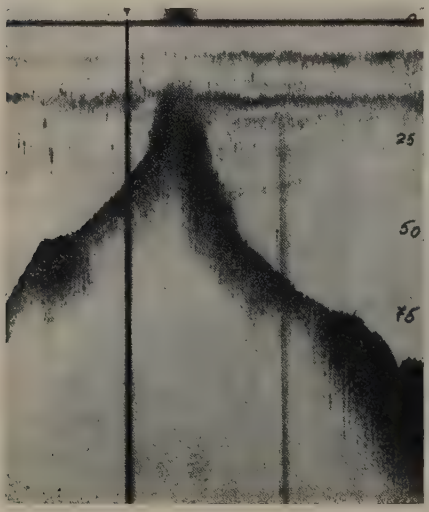


FIGURE 3.6 - Echo sounder record of ghost bottom.

FIGURE 3.7 (right) - Simplified diagram of echo from two fish separated by half the length of the sound pulse. The pulse has just passed the fish, and the echoes are on their way.

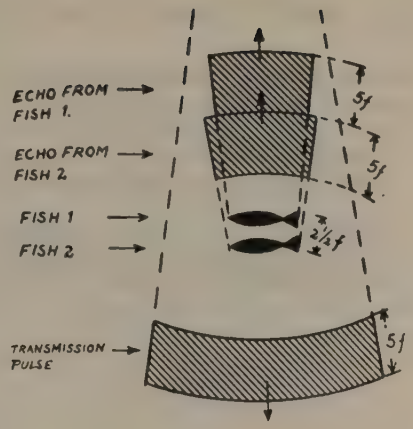


FIGURE 3.8 (below) - Echo sounder record of single fish using three different pulse lengths: 1 millisecond (left-hand trace), 3 milliseconds (middle trace), and 12 milliseconds (right-hand trace).

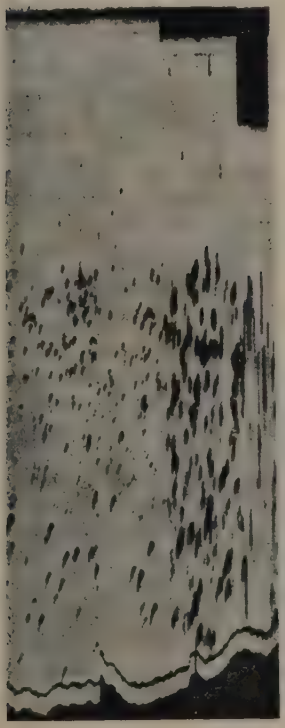


FIGURE 3.9 (right) - Comparison of echo sounder records of a herring school, obtained with an echo sounder using 100 kc/s sound frequency and 0.08 millisecond pulse length (above), and correspondingly 30 kc/s and 0.5 millisecond (below). The higher resolution of the upper record is clearly evident. (From Fisheries Laboratory, Lowestoft, United Kingdom.)

individual fish in dense concentrations. Figure 3.9 shows a herring school recorded on a 30-kHz echo sounder with a pulse length of 0.5 millisecond and wide beam (lower trace), and on a 100-kHz echo sounder with a pulse length of 0.08 millisecond and narrow beam (upper trace). The vertical resolution is evidently much greater in the latter.

Characteristics of single fish records. The recordings of single fish will vary greatly in appearance between different types of echo sounders and different operating conditions. With the vessel lying stationary, single fish remaining in the sound beam will be recorded as continuous line traces, as shown in Figure 3.10A. At slow speeds the lines shorten and become curved (Figure 3.10B) and at high speeds they appear as dots or points (Figure 3.10C). The reason for this is that the number of echoes obtained from each individual decreases as its speed of travel through the sound beam increases. The beam angle in the ship's direction of travel will also influence the appearance of single fish traces: the wider the beam, the longer the individual traces.

The curved line or inverted v-shaped traces appearing in recordings at relatively low speed (or with a wide-angle transducer even at high speed) are typical of single fish traces. They are caused by the fact that the distance between fish and transducer is greater when the fish is near the edge of the beam than when it is directly under the ship. Figure 3.11 shows this. When the ship is pitching or rolling this characteristic shape may be difficult to detect.

Although it is desirable to use a narrow beam for quantitative evaluations, it might be useful for identification purposes that a well-defined trace of individual fish be produced. Distributions of trace lengths are also important for estimating sampling volume (Section 4).

As shown in Section 1, the echo strength of a target of a given strength decreases as the fourth power of its range from the transducer. It is therefore necessary to adjust the gain on the amplifier to maintain the

FIGURE 3.10 - Left (A): Echo sounder traces of single fish when vessel is stationary. Centre (B): Single fish traces at slow speed. Note inverted v-shape. Right (C): Single fish traces at full speed.

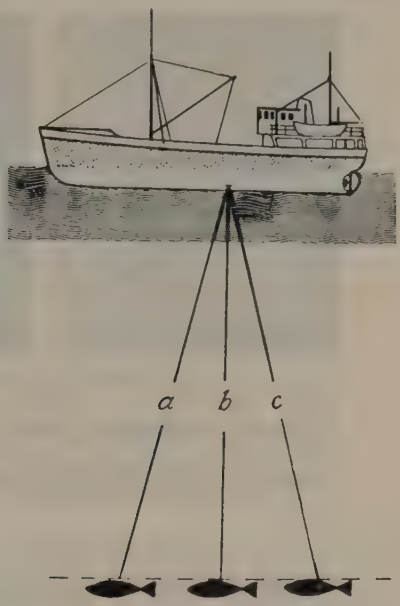


FIGURE 3.11 - One fish in three different positions during passage of sound beam. The oblique distances *a* and *c* are greater than the vertical distance *b*.

recorded signal strength from targets at increasing ranges at the same level. Some types of echo sounders automatically compensate for the decrease in signal strength with depth by the introduction of a TVG system. An example of an echo record taken with such a system is shown in Figure 3.12.

The use of TVG is important when measuring the target strength of individual fish at sea, and in discriminating between different types and sizes of fish throughout the depth range. If TVG equipment is not available, it is often advantageous to run two echo sounders (of different transmission frequencies) simultaneously, one to cover the upper water layers at a relatively low gain, and the other to cover the deeper layers at a relatively high gain. Such a procedure is often facilitated by the fact that fish concentrations giving rise to single echoes are frequently distributed within a certain depth interval (as shown by the record of large spawning cod from the Lofoten area reproduced in the upper trace in Figure 3.15).

Records of fish in layers and schools. When fish density exceeds the limit of the power of resolution of the echo sounder used, the record takes the form of a multiple-echo trace, which may appear as a layer or as a distinct solid trace. There is, of course, a continuous transition from dispersed layers or bands — where the echoes from a large number of

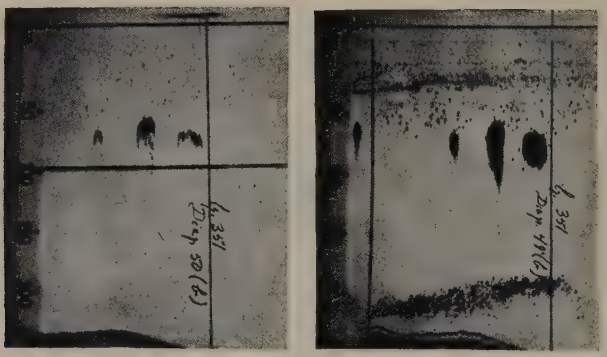


FIGURE 3.12 - Comparison of echo sounder records of the same targets, without (left) and with (right) time-varied-gain. Note that the fish layer (probably mackerel) at 200 m depth is completely missed in the left-hand picture. (Note: the linear gain has also been increased in the second picture.)

single individuals can still be identified — to dense layers and schools. Figure 4.3 in Section 4 shows some examples of different types of layers and distinct schools of small herring, while Figure 3.13 shows the same for adult herring. One should note that paper recorders do not, *per se*, give adequate information on the density of fish in such layers or schools.

A usual feature of the layer-type traces often produced by fish is the presence of single fish traces at the upper and lower borders of the layer. This is clearly shown in Figure 3.13 for herring. This feature can be used to distinguish layer traces produced by fish from those of smaller organisms (fish larvae and other plankton organisms), whose individual target strengths are below the detection threshold of the echo sounder (see below). Measurements of signal strengths from individual targets may assist in identification of the fish present in the layers.

As opposed to layer traces, well-defined schools of pelagic fish do not usually "thin out" at the edges. This is shown by the traces of herring schools in Figure 3.13 (upper trace), and again in Figure 3.14, which shows schools of anchovy. A typical feature of echo records of dense pelagic schools is that their traces are often followed by a "tail" of sound reverberation. The sound is scattered inside the school, and some of it is reflected back to the transducer after the return of the dire t echo of the deepest part of the school. The height of the trace of a school is therefore not a direct measure of the true height of the school. A reverberation can be distinguished in Figure 3.14 and also quite clearly in the upper trace in Figure 3.9.

Many fish species form schools in daylight and disperse into diffuse layers in darkness. These layers often allow recording of single fish traces.

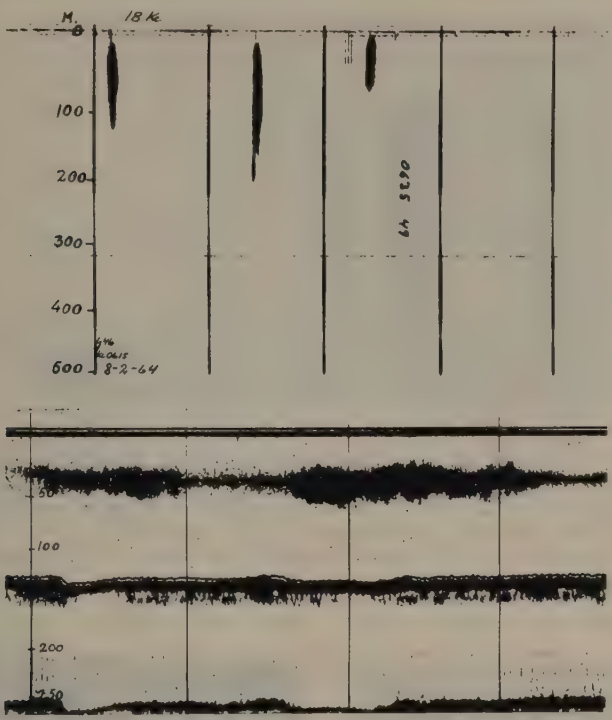


FIGURE 3.13 - Echo sounder records of schools and layers of large adult herring. The distance between vertical lines represents one nautical mile.

Examples for young and adult herring have been shown earlier; others, for cod and anchovy, are shown in Figure 3.15.

In addition to the layer-type traces recorded by fish concentrations, described above, other types of diffuse layer traces are commonly produced by dense concentrations of smaller organisms such as fish larvae and other plankton organisms, often associated with a discontinuity layer in the water column. They appear as very finely grained "clouds" or "layers" and they are often recorded over large areas. In general such layer traces are produced by organisms occurring at high densities, and whose individual target strengths are below the detectable limit of the instrument. In this respect they differ from the layer-type traces produced by fish in not showing records of individual targets in association with the main layer traces. Also, the character of the trace does not change significantly if the vessel slows down or stops.

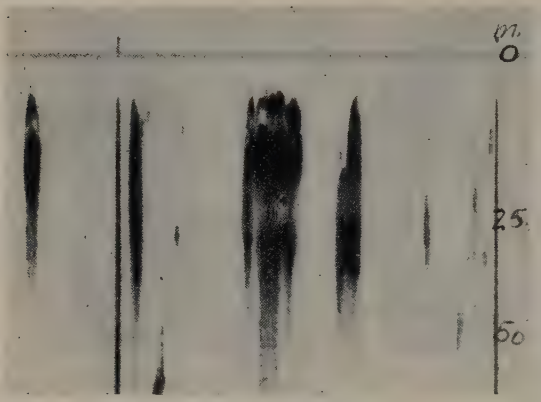


FIGURE 3.14 - Echo sounder record of dense school of anchovy.

There is a graduation in the character of layer traces from this fine diffuse type to the layers produced by adult fish. 0-group fish, for example, are often distributed within fairly narrow depth limits and are therefore recorded as layer traces, but, like the traces of larger fish, they can usually be distinguished from the finer type of trace produced by fish larvae and other small organisms by the presence of individual traces in association

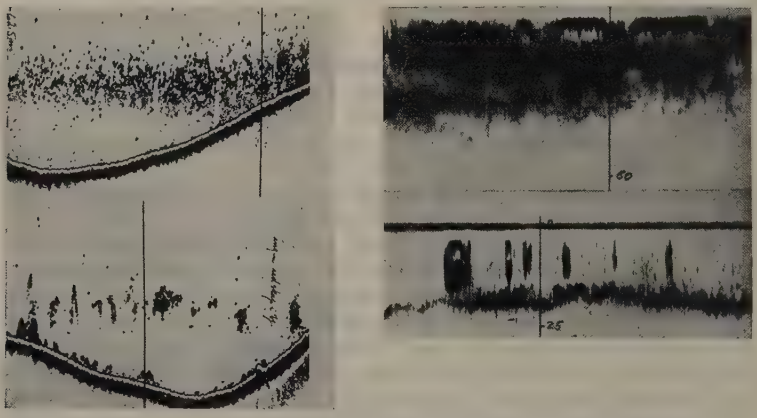


FIGURE 3.15 - Left: Echo sounder record of big spawning cod on the Lofoten Banks, in layer during the night (top), and in schools during daylight (bottom). Right: Echo sounder records of anchovy. In broad layer, with thinner plankton layer underneath, during the night (top). Recording of the same area in the morning, with the anchovy now schooling, but the plankton still in layer (bottom).

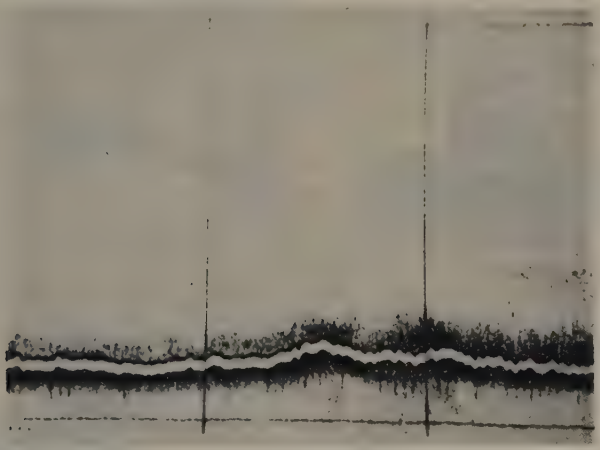


FIGURE 3.16 - Typical echo sounder record obtained from a fishing ground for deep sea shrimp at night, and which shows shrimp lifting off the bottom.

with the layer trace. Further, the traces of 0-group fish which are of a layer type in darkness usually change to a more discreet school-type trace in daylight.

An interesting echo record which appears as a diffuse layer is given by deep sea shrimp. It is well known that they rise from the seabed at night, and Figure 3.16 shows a typical record obtained with a high sensitivity instrument.

A phenomenon of minor importance, which may puzzle an observant operator, should be mentioned here. When surveying an area where small dense schools occur in the upper water layers, the side-loops of the echo sounder transducer may produce echoes which will take the form of long inverted v-shaped traces on the recorder. This phenomenon can be checked with a sonar instrument.

3.3.1.4 *Records of fish close to the seabed*

Fish very close to the seabed are more difficult to detect than pelagic fish because of the additional complication of distinguishing between fish and bottom echoes. This is illustrated in Figure 3.17, which shows that there is a "dead field" in the sound beam close to the seabed. If the bottom is uneven, the extent of the dead field increases.

Because the paper recorder presents both fish and bottom echoes as a black signal, they become confused. The white-line system of presentation assists in distinguishing between them by separating the seabed signal

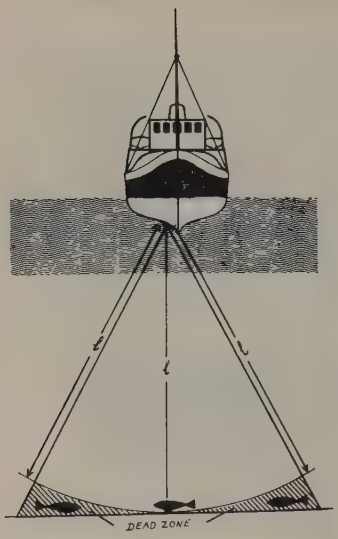


FIGURE 3.17 - Diagram illustrating the dead field in the sound beam close to the bottom.

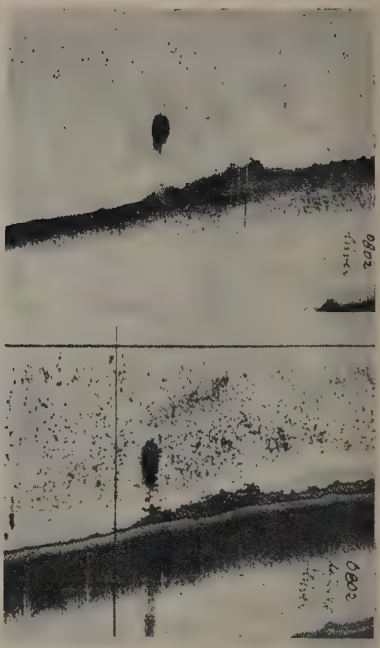


FIGURE 3.18 - Echo sounder records of the same target with and without white-line effect.

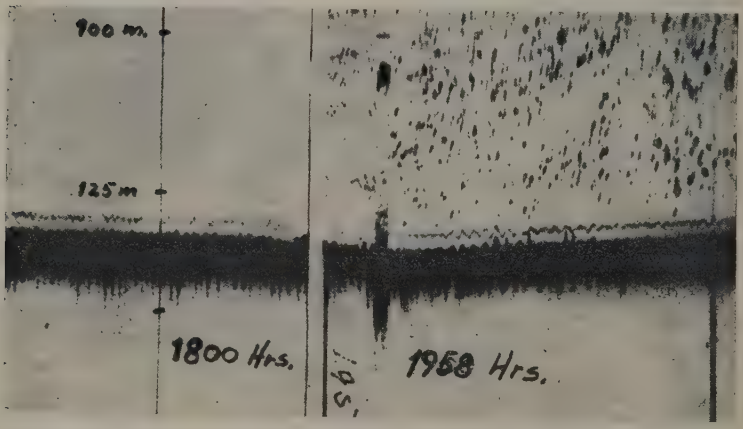


FIGURE 3.19 - Echo sounder records from hake trawling, with good catches during afternoon (left), and showing hake lifting off the bottom in the same area after sunset (right).

from the weaker signal of fish close to it. This is illustrated in Figure 3.18, where the upper trace shows fish and bottom signals confused and the lower one their signals separated by the white-line effect. If fish are very close to the seabed, even if the white-line system is used it may not be possible to distinguish their echoes from the seabed. An example is shown in Figure 3.19.

The size of the dead field can be diminished by reducing the width of the echo sounder beam and/or the pulse length. With a pulse length of 5 to 8 cm, a fish like a cod should always be detected at least on the axis of transmission. The problem may be more or less completely solved in future with the use of sector-scanning sonars (see Section 5).

One way of detecting fish close to the seabed is to use an echo sounder with a "slanting" sound beam, that hits the seabed not vertically but at a relatively low angle. Then, echoes from fish near the bottom may, under favourable conditions, be distinguished from the relatively weak bottom echo.

3.3.1.5 *Sources of extraneous and spurious echo records*

The proper functioning of an acoustic instrument may be affected, or at times completely prevented, by various types of "noise" on board the vessel. They may be of electric or acoustic origin, and the problems connected with them are to a great extent related to the skill and care used in choosing the location of the transducer during the installation of the equipment. One of the most common of these sources of noise is propeller interference. Propeller noise will show up in a regular pattern and is often more prominent at a certain number of revolutions or at special pitch-settings. An example is shown in Figure 3.20.

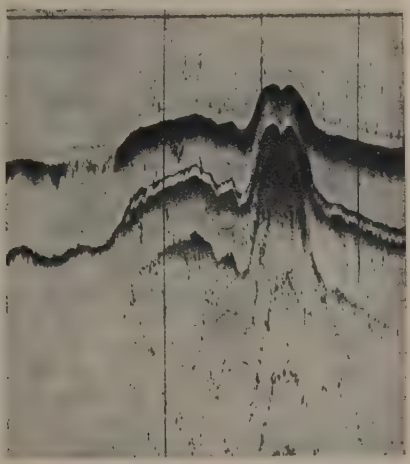


FIGURE 3.20 - Echo sounder record showing interference from propeller noise.

An important type of interference is the side-echo produced by side-loops from a steeply sloping seabed. In narrow and shallow waters these may look like fish schools. In special cases the largest part of the sound energy may be reflected away from the bottom at a low angle so that it does not reach the ship, and the echo picked up by the transducer may show a diffuse shadow more like a fish school than a distinct bottom echo. The dead field in the sound beam is also increased when passing a very steep bottom inclination.

Whales produce sounds in the sea which are recorded on acoustic instruments. Figure 3.21 shows various types of pips and squeaks produced by a school of whales on an echo-ranging set. Similar signals are also recorded on echo sounders.

Finally it is worth noting that air bubbles in the water immediately under the transducer may completely prevent the emission of the sound. This may occur when the vessel is pitching heavily in bad weather, and also when it crosses the wakes of other vessels or goes astern.

3.3.2 Horizontal echo-ranging sonar records

3.3.2.1 *General characteristics*

The important function of horizontal echo-ranging sonar in survey work on pelagic fish is that the area covered by the search can be much greater than that covered by a vertical echo sounder, and additional information can be obtained on the behaviour and distribution of the fish.

Sonar records are fundamentally different from those of echo sounders, but for an inexperienced operator it may be a help to think of this equipment as a "horizontal echo sounder."

A significant feature of most of these instruments is that the transducers can be trained in any direction from the ship and the appearance of the echo traces differ accordingly. Figure 3.22 illustrates typical patterns of records obtained when the transducer is fixed in a forward direction and at 90° to starboard (or port) respectively. In shallow water an uneven seabed will give distinct echoes and the figures show the traces produced by three ridges of the seabed with the transducer in the two positions mentioned above.

In the forward position of the transducer, the trace approaches the zero line until it disappears when the target passes underneath the bottom part of the beam. This depends, of course, on the depth of the target as well as on the beam angle. With a known beam angle the depth can be approximately estimated, which is of some use for assessing the depth of fish schools. It is also evident from this figure that the rate of approach is indicated by the angle between the trace line and the zero line, and it depends on the relative movement of the vessel with respect to the target. Knowing the vessel speed one can estimate, theoretically at least, the movements of the target, but in practice movements of fish schools can

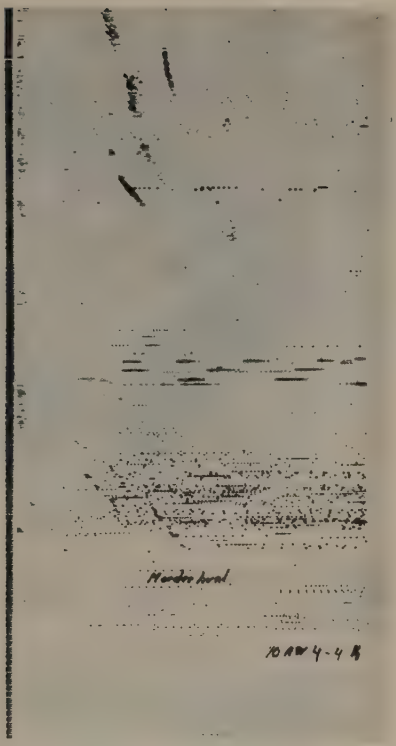
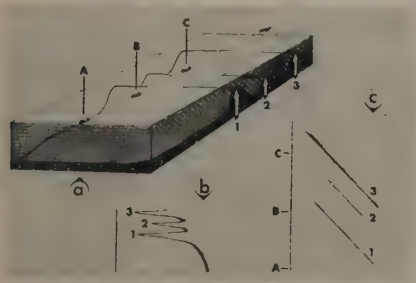


FIGURE 3.21 - Signals produced by a school of whales on a horizontal echo-ranging recorder.



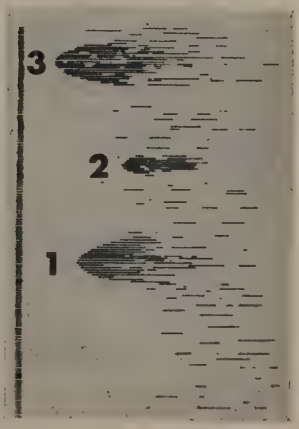


FIGURE 3.22 - Left: (*a*) Vessel with the echo-ranging sound beam fixed in forward direction; (*b*) depth sounder recording of the same area; (*c*) echo-ranging recording of the same area. Right: Echo-ranging record from the same area, but with sound beam fixed at 90° to starboard or port.

FIGURE 3.23 - Vessel passing a school of fish with the sound beam (transducer) fixed at 90° to starboard.

best be observed with echo-ranging sonar from a stationary vessel, or by circling around a school and observing its position in relation to the wake of the ship.

Figure 3.23 illustrates schematically the recording of a fish school by echo-ranging equipment when fixing the beam at 90° to starboard. It is obvious that the width of the trace in the lengthwise direction of the recording paper depends not only on the size of the fish school, but also on the horizontal beam angle, the speed of the vessel and paper speed.

3.3.2.2 *Echo-ranging records of the seabed*

In contrast to the echo sounder the horizontal echo-ranging sonar usually cannot give much useful information on the seabed, as this is recorded by a normally operated echo ranger only in relatively shallow waters. Figure 3.24 shows a record containing various types of bottom echoes. The first trace (A) following the zero line is the side-loop echo from the bottom. This will correspond more or less directly with the true bottom depth. The second heavy trace (B) is the echo from the main beam where it hits the bottom at some distance from the ship.

Bottom echoes are easily recognized by comparison with the depth recorded on an echo sounder, and by the fact that they do not vary significantly with changes in the training of the beam. Shore echoes and echoes from peaks and ridges on the sea bottom may, under certain conditions, give rise to greater difficulties of identification. However, for his classification of echoes, a trained operator makes use not only of the graphical record but also of an audible signal by which it is often possible to distinguish between echoes from different types of targets.

3.3.2.3 *Records of fish*

The appearance of fish records on the horizontal echo-ranging recorder will differ with the search programme that is being applied. A normal programme for the widest possible coverage is to search between about 60° port and 60° starboard with sound emissions at every 5°. Modern instruments have automatic search programmes of this type. The type of record obtained when passing a number of fish schools with a side-to-side sweep is shown in Figure 3.25. Traces are produced as the beam passes the schools in 5° steps. The same target may appear two or more times in the echo record depending on its distance from the ship's course and the range at which it was first detected. This type of search programme is, therefore, not suitable for obtaining a count of the number of schools recorded, and assessing their range and, roughly, their size. However, it is the most effective detection programme and Figure 3.26 shows a record of a side-to-side sweep, during the process of a vessel homing on to fish schools.

Figure 3.27 shows the echo-ranging and subsequent echo sounder records of schools which were approached and passed over. It will be noted that the size of the echo sounder traces of the schools do not always correspond to the strength of the echo-ranging ones. This is usually because it is difficult to "hit" the school with the ship so that it passes through the centre of the echo sounder beam.

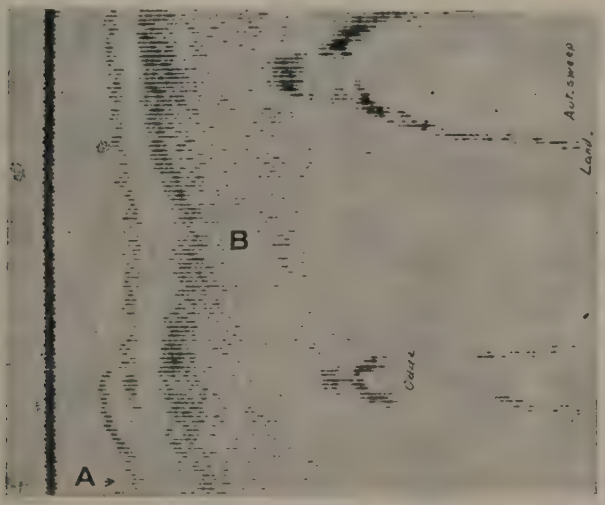


FIGURE 3.24 - Record of echo-ranging echoes from the seabed and the shore.

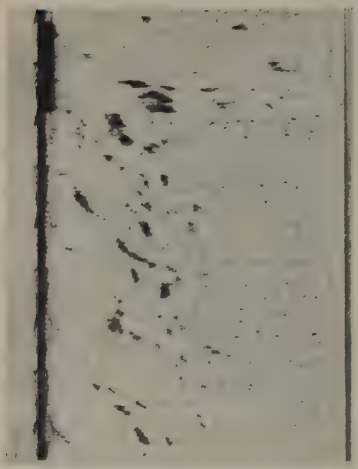


FIGURE 3.25 - Echo-ranging record when passing a number of good recordable fish schools, with a search programme of side-to-side sweep.

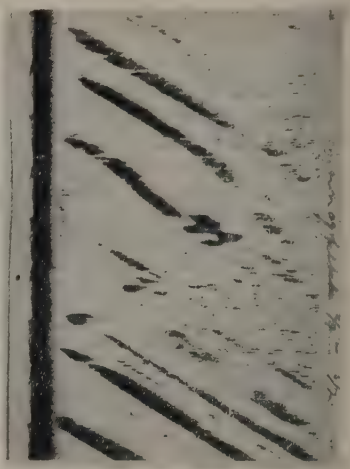


FIGURE 3.26 - Echo-ranging record of side-to-side sweep interrupted by instances of the vessel turning toward and approaching schools.

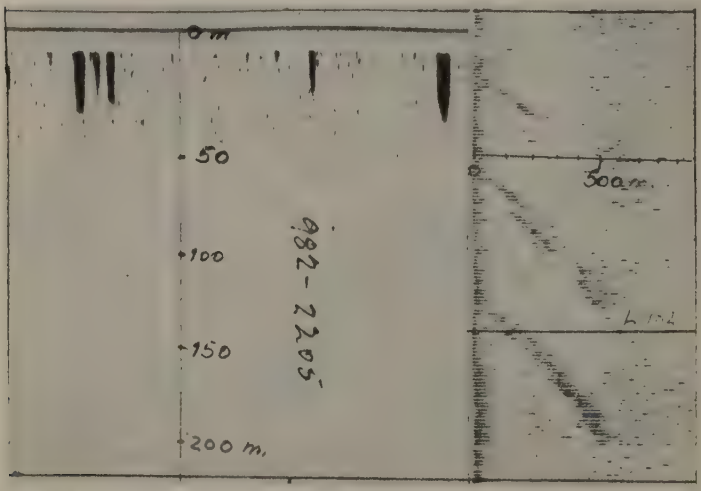


FIGURE 3.27 - Records on echo ranger (right-hand trace) and echo sounder (left-hand trace) of schools approached and passed over by vessel.

FIGURE 3.28 - Echo-ranging record of fish school being approached, using first (lower trace) the full range of the instrument, and (upper trace) the short range.

A survey programme frequently used for pelagic schooling fish is to have the transducer at a fixed angle of 45 to 90° to port or starboard. This will allow a reasonably good coverage over the course, at the same time providing relatively long traces of the targets and hence information regarding their number and classification.

Some horizontal echo-ranging instruments have, in addition to their full-range scale, a short scale for use at distances of a few hundred metres. Figure 3.28 shows a record of a fish school being approached at full range. When closing in, the short range with a higher transmission rate and faster pen speed was used. The shorter range should also be used when searching or surveying in water where sonar conditions are poor so that effective range of coverage is severely restricted. The higher transmission rate of the shorter range interval will then ensure more echoes and so more information from each target.

If the transducer is tiltable or if a separate vertical transducer can be used, schools can be approached and then recorded vertically with the same echo-ranging equipment. Figure 3.29 shows a record of this operation carried out with an instrument used for short-range work. However, because the technical requirements of echo rangers and echo sounders are so different the use of a combined dual-purpose instrument is not recommended. Simultaneous operation of the two types of instrument is usually advisable.

Under favourable conditions, schools of fish close to the seabed can be detected by echo-ranging equipment. The seabed must be reasonably

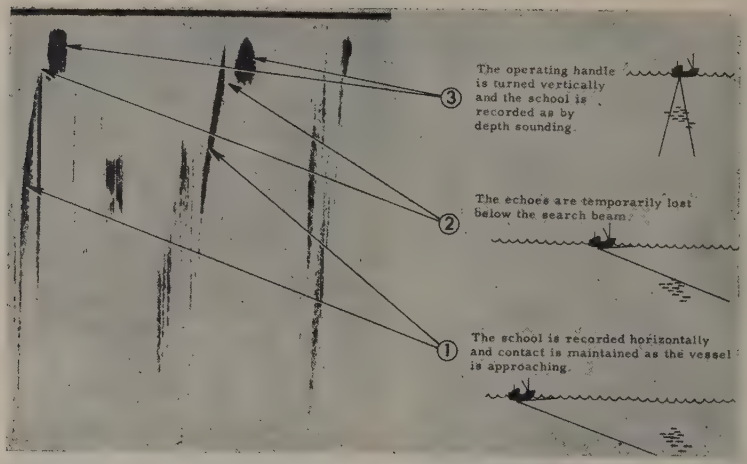

The operating handle is turned vertically and the school is recorded as by depth sounding.
3
The echoes are temporarily lost below the search beam.
2
The school is recorded horizontally and contact is maintained as the vessel is approaching.
1

FIGURE 3.29 - Records and schematic diagram of how schools can be approached with horizontal sound beam and recorded vertically with the same beam in instruments with tiltable transducers.

level and smooth. Figure 3.30 shows a record of fish schools being approached by a vessel using different echo-ranging scales (left) and the subsequent trace of the schools on an echo sounder (right).

Finally, reference should be made to another type of recording of echo-ranging signals, that is, their presentation on a PPI screen. This has the advantage of giving a correct, two-dimensional image of the distribution of the targets relative to the vessel, similar to the well-known picture obtained on a radar screen.

In Section 1, anomalies in the propagation of sound by refractions of the sound beam under special oceanographic conditions have been described. Such refractions may greatly affect the range of detection. The vertical temperature gradient is the factor of greatest importance for the refractions and hence the range. A bathythermograph record of the upper water layers may, therefore, give important information for assessing the effective range. Generally speaking, echo-ranging conditions are best when there is no vertical temperature gradient or a slight increase with depth. This condition will, in most cases, occur in winter and early spring. Summer conditions with a warm surface layer and a sharp thermocline near the surface may result in a considerable reduction of the range because of a sharp refraction of the beam downward. The approximate, effective range in an area can, in practice, be assessed empirically quite rapidly if a rough evaluation of the target strength of the recorded schools can be obtained, for instance from subsequent echo sounder records, or from echo-ranging

contact at a very short range. One should always keep in mind that at some distance the strength of the echo does not only depend on the target strength of the object that is being recorded, but also very much on the sonar conditions in the sea.

3.3.2.4 *Records of echoes from extraneous and spurious sources*

Various types of disturbing signals arising from electric or acoustic "noise" produced on board the vessel itself may affect echo-ranging records in the same way as they affect echo sounder records. There are, however, a number of disturbing "nonfish" records peculiar to echo-ranging records. Since signals may in most echo-ranging sets be presented as audible sound as well as paper records, the transducer-receiver units take the function of a microphone by which certain kinds of underwater sound may be heard. Propeller noise is one of the strongest and most conspicuous of these. The propeller noise of one's own ship may, incidentally, be used as a rough check that the training indicator of the transducer is correctly set: the noise should have a maximum when the transducer is pointed directly astern.

Sea water containing small air or gas bubbles gives good echoes, and

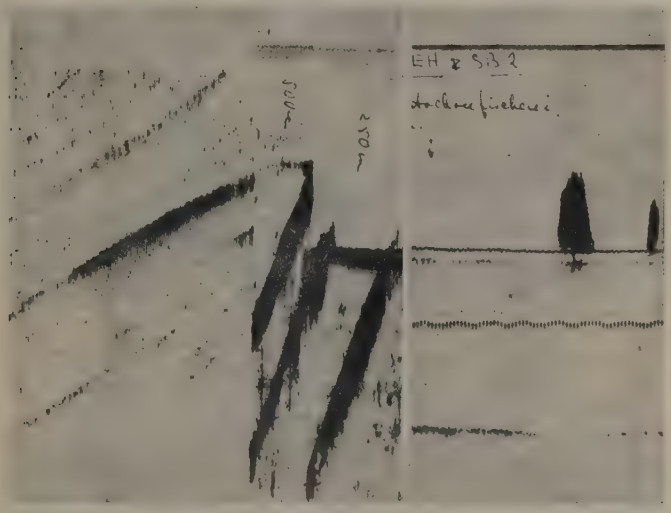


FIGURE 3.30 - Echo-ranging and echo sounder records showing fish schools on the bottom being approached while using three different basic sonar ranges, and the same schools appearing on the vertical echo sounders. Note that the sonar traces of the fish schools disappear just after the bottom echo from the main sonar beam appears on the record. This is because the schools are located close to the bottom.

records of the wakes of steaming ships may easily be mistaken for fish schools. In a rough sea, with big breakers, aeration of the water may cause the sonar beam to be reflected. Three or four good echoes may be received from such breakers, even at considerable distance, but the contact is usually quickly broken.

Reverberation is the shifting sound heard after a pulse transmission, and the small dots and dashes recorded on the echo record. Thus it consists of a sequence of small echoes. It is caused by echoes from small sound scatterers in the sea. Over deep water, reverberation can give useful information on the effective range in an area because these faint echoes are usually only produced in the surface layers and not from a beam refracted downward. Figure 3.31 shows two records of reverberation, one indicating a long and the other a relatively short range. The sound pitch of the audible record of reverberation (and other echo signals) on a steaming ship differs in relation to the training of the transducer relative to the course of the ship. It is high in the forward and low in the astern direction because of the Doppler effect on the sound waves.

Large vertical or horizontal temperature gradients in the sea may give rise to stratified echoes. Because of the irregular, often wavy, pattern of such strata, the echoes from them may vary considerably with distance and they may on occasion be confused with stationary targets by an inexperienced operator. However, usually they are not much affected by a change of direction of the beam, being detectable around 360°, and they do not give the sharp and distinct echoes characteristic of fish schools.

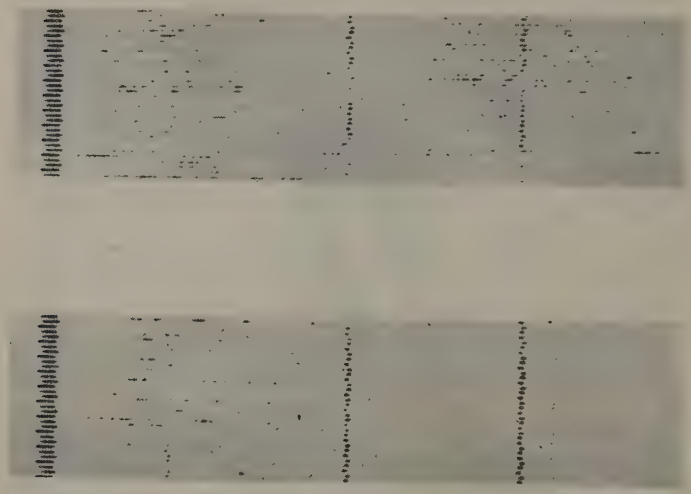


FIGURE 3.31 - Sonar records demonstrating long and short reverberation.

Figure 3.32 shows a record of stratified echoes; when they are present the range of the equipment is often short.

Finally, it is worth mentioning interference from other acoustic instruments. Even if working on a different sound frequency, an echo sounder may give rise to interference on echo-ranging equipment and vice versa. Where several vessels using acoustic instruments operate within a small area interference may be severe, but neighbouring boats are usually visible and interpretation of the records is possible.

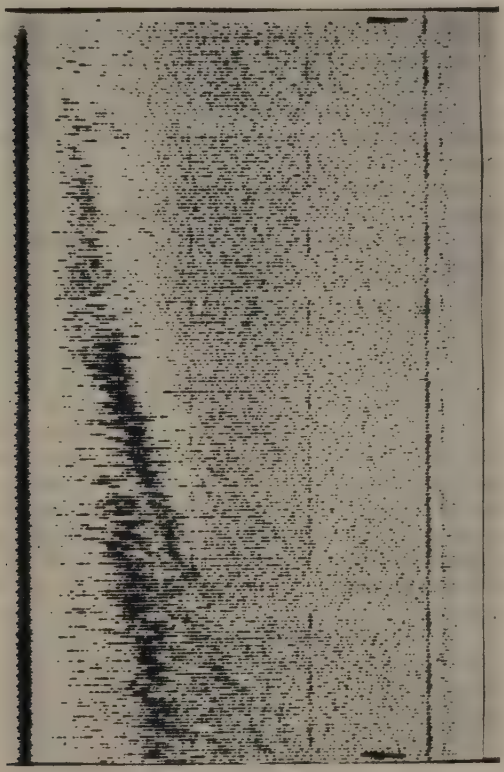


FIGURE 3.32 - Sonar records of stratal echoes.

SECTION 4. ABUNDANCE ESTIMATION

4.1 The history of echo surveying

The first systematic trial using an echo sounder to detect fish was carried out in 1933 (Balls, 1948). Balls used an echometer to search for herring in the North Sea, and an outstanding feature of his results was: "the steadily increasing efficiency in the use of the echometer for locating herring during the successive summer seasons." The first echograms of fish were published by Bokn (1934), Edgell (1935) and Sund (1935). Sund, who clearly saw the advantages of the echo sounder as a tool for fishery scientists and fishermen, carried out the first regular echo surveys on spawning cod in the Lofoten area (Sund, 1938). He made charts of abundance of cod and advised fishermen about the positions and depths where the largest concentrations of fish were found. Sund's estimates of abundance were based on a purely subjective visual grading of the paper record. Runnstrøm (1941) used the same technique on the herring spawning grounds.

In the period 1940-55 numerous studies were carried out on fish distribution, abundance and behaviour by observing fish with echo sounders and sonars, and considerable knowledge was gathered with respect to diurnal and seasonal changes in distribution pattern, migration routes, etc. (Cushing, 1952), (Hodgson and Fridriksson, 1955). The method used by Sund (1938, 1943) and Runnstrøm was extended by Cushing (1952). He obtained estimates of the horizontal extent of the targets by measuring, with a binocular or a ruler, the width of the marks on the paper record. Thus each transmission was examined for the presence or absence recordings, a method which can be, and has been, used to give fairly reliable estimates of relative fish abundance.

The next stage in the development of these methods was the recognition of single fish as "fingernail" traces on the paper record. Saetersdal (1955) recognized traces of medium-sized single cod down to 170-180 m, and Midttun and Saetersdal (1957) made a first attempt to give an absolute estimate of abundance. They estimated the number of fish within a limited area in the Barents Sea by counting individual fish traces on the recording paper. A step toward more accurate signal processing was taken by Richardson *et al.* (1959), who developed a method for estimating the abundance of cod on the bottom on the Svalbard Shelf. Signals were counted and their amplitudes measured in a scan of one to two fathoms

off the bottom on a cathode-ray tube. An attempt was also made to correlate trawl catches and signals, following the lead set by Balls (1948) who had already in 1933 initiated this technique.

During the 1960s several automatic counting devices were introduced, which worked in conjunction with echo sounders: the pulse counter (Mitson and Wood, 1961), the cycle counter (Dowd, 1968), the echo integrator (Dragesund and Olsen, 1965; Bodholt, 1969), and the pulse height analyser (Craig and Forbes, 1969). The pulse (or cycle) counter measures the number of returned pulses (or cycles). As long as the fish are recorded as single fishes the true number of recorded fishes are measured. However, when fish schools are recorded the pulse (or cycle) counter measures the depth extension of the school. The echo integrator integrates squared voltages, thus the output from the instrument can be considered proportional to fish density as long as this follows the "square voltage law." The pulse height analyser generates frequency distributions of echo amplitudes in different range slices, and it exploits the theory to the full when single fish are recorded. These methods are dealt with in detail later in this section.

In spite of the development in signal processing, and the large number of echo surveys carried out during the 1960s, very few estimates of absolute abundance of fish have been made. Truskanov and Scherbino (1964, 1966) and Scherbino and Truskanov (1966) made stock assessments of the Atlanto-Scandian stock of herring. Their estimates, which agreed completely with those obtained by other methods, were based on oscilloscope readings. The relation between oscilloscope readings and fish densities was established by photographing fish schools, and this showed empirically that the squared echo voltage was proportional to the fish density. Cushing (1968) estimated the number of hake in a layer close to the bottom in an area off southwest Africa.

An important echo survey has been carried out on 0-group fishes in the Barents Sea. The work started on 0-group herring (Dragesund, 1959; Midttun, 1959) and was later extended to include 0-group fishes of other important species. Since 1965 this work has been carried out as a multiship survey with participating research vessels (up to five) from Norway, the United Kingdom and the U.S.S.R. (Dragesund, 1970a). Dragesund (1970b) obtained a good correlation between the relative echo abundance of 0-group herring and the strength of the same year-classes in the adult stock. The Peruvian Eureka programme on anchovy (Villanueva, 1970), which is carried out several times a year by 15 to 20 purse seiners equipped with echo sounders, gives quite synoptic charts of anchovy distribution. The Eureka programme is a cooperation between fishermen and scientists and in operation is similar to the Icelandic herring search (Jakobsson, 1970).

Recently Smith (1970) introduced a new method in echo surveying. He used the sonar as a horizontal echo sounder (90° training) for counting schools and measuring school sizes. By using commercial catches to obtain an index of average school size in tons, he was able to give figures of absolute abundance.

So far, most of the effort in echo surveying has been directed toward more reliable estimates of fish density within the volume searched. Considerably less work has been published on survey design, although this is not less important. Craig (1969) concludes that each investigator makes a reasonable study of the characteristics of the important species for the area and season concerned before planning major survey exercises. When surveys are to be repeated over a long period of time, then the material collected during one survey should be carefully analysed before the next is initiated, as the knowledge gained from the first will improve both the tactics and the technique of the next. Craig suggests ways of looking at the information that may be helpful in planning echo surveys.

4.2 Theoretical background

The distribution of echo strengths from a fish population is a fundamental factor in making quantitative assessments of that population. All methods of acoustic fish stock assessment require some knowledge of echo strengths, and the more information available the more accurate the assessment will be. In the crudest method, simply distinguishing between presence and absence of signal, a knowledge of the minimum signal required to mark the recording paper can allow remarkably useful population estimates to be made, while very high precision is possible if modern electronic techniques are used to measure echo strengths accurately.

Clearly, before conclusions can be drawn from observations of echo-strength distribution, it is necessary to know the expected distribution from a known fish population. The first step, while fundamental, is easily made if the parameters of the acoustic equipment are known. The inverse process of calculating fish population from the observed distribution is not difficult in principle, but demands some mathematical insight. There are two basic situations to consider: one where each echo is from a separate fish, and the other where many echoes come either from several fish simultaneously or from a scattering layer of small organisms. These will be treated separately.

It should be noted at this point that where multiple echoes become appreciable fish density is quite low. For example, if an echo sounder has a transducer beam-width of 10°, and a pulse length of 1 millisecond, then the pulse volume at a depth of 200 m is about 900 m^3. Thus, if there is an average of more than one fish within such a volume, many multiple echoes will be received.

4.2.1 Single fish echoes

4.2.1.1 *Echo-strength distribution*

Consider first a situation where fish are distributed so that only one fish contributes an echo at any one instant. For simplicity, assume that

all fish have identical target strengths, and that they are randomly distributed with a density of N per cubic metre. Assume echoes have been obtained from a range slice ΔR, which is sufficiently small to make the total transmission loss ($R^4\, e^{2\beta R}$ or 40 log $R + 2\alpha R$ dB) constant. θ and φ are the angular coordinates of a target in the beam as defined in Section 1, and are measured in radians.

The received echo level at the sounder is given by the usual sonar equation

$$EL = SL + TS - (40 \log R + 2\alpha R) + 20 \log b_{(\theta,\varphi)} \quad \ldots\ldots\ldots(1)$$

or $$I = I_o \cdot \frac{\sigma}{4\pi} \cdot \frac{e^{-2\beta R}}{R^4} \cdot b^2{}_{(\theta,\varphi)}$$

In either case, assuming that target strength, source level and range are constant, one can write

$$EL = K + 20 \log b_{(\theta,\varphi)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

or $$I = kb^2{}_{(\theta,\varphi)}$$

Since the fish are assumed to be randomly distributed, the number of echoes from each element of solid angle of the beam will be the same, and a plot of solid angle Ω against $b^2{}_{(\theta,\varphi)}$ or 20 log $b_{(\theta,\varphi)}$ will give the relative number of echoes as a function of echo strength. Figure 4.1A shows these curves schematically. The ordinates of Figure 4.1A represent the solid angle within which echoes of intensity greater than the corresponding value of $kb^2{}_{(\theta,\varphi)}$ or $\{K + 20 \log b_{(\theta,\varphi)}\}$ will be obtained, the corresponding number of echoes received from each transmission being $NR^2\,\Delta R\Omega$. The relative number of echoes of each intensity can be obtained by plotting the inverse of the slope of these curves against b^2 or 20 log b, resulting in the curves of Figure 4.1B.

For a circularly symmetrical beam, the solid angle Ω is given simply by $\Omega = 2\pi(1\text{-}\cos\theta) = \pi\theta^2$ to a sufficiently high degree of accuracy, for angles of less than about $\frac{\pi}{4}$ radians or 45°. Thus it is a simple matter to plot $\pi\theta^2$ against the theoretical value of $b^2{}_{(\theta)}$. For practical transducers it is better to measure the directivity directly, perhaps by plotting contours of constant intensity against angular distance from the beam axis, and measuring the angular area or solid angle within each contour. Side lobes are dealt with simply by adding the solid angle occupied by each side lobe at a given intensity to that of the main beam.

In many cases, voltage levels of received signals are measured, and here it is more appropriate to plot Ω against $\delta^2{}_{(\theta,\varphi)}$ instead of $b^2{}_{(\theta,\varphi)}$, resulting in Figure 4.1C, where the ordinates now correspond to the solid angle appropriate to a particular voltage level. The curves for the loga-

rithmic case are unchanged. In practice, it is much easier to work in decibels, since the appropriate curves for different target strengths or ranges can be obtained simply by adding the appropriate factor K to the abscissae of the curve, whereas if voltage or intensity is used directly, the whole scale of the curve must be changed by multiplying by the factor k.

Another case of practical importance is that where the maximum echo from each fish is measured. Here, the intensity of each echo is measured on the athwartships axis of the beam, with the result that the fish are effectively distributed uniformly in angle θ instead of solid angle Ω. Similar curves to those of Figures 4.1B or 4.1C can be prepared in this case by plotting θ against $b^2_{(\theta)}$ or $\delta^2_{(\theta)}$, or their decibel equivalents. Figure 4.1D shows the logarithmic curve for the same transducer as before, for comparison. The actual numbers of echoes in this case are given by $2NR\Delta R\theta$ per metre steamed.

4.2.1.2 *Sampling volume*

The concept of sampling volume for an echo sounder depends on how the sounder is used, resulting in two possible ways of measuring sampling volume. Where each transmission is considered to give a separate sample of the population, then the sampling volume is given by $R^2\,\Delta R.\Omega'$, where Ω' is the solid angle within which echoes from a given target strength will be above the minimum detectable level. The total sampling volume is then the product of $R^2\,\Delta R.\Omega'$ and the total number of transmissions. On the other hand, if fish traces are being counted from a paper record, the sampling area of the beam is $2R\Delta R\theta'$, where θ' is the athwartships angle within which echoes from a given target strength will be above the minimum detectable level. The total sampling volume in this case is the product of $2R\Delta R\theta'$ and the distance steamed.

In either case, the appropriate angle or solid angle is simply found by considering Figure 4.1A or Figure 4.1D. If I' is the minimum detectable signal, and $(b^2)'$ is the corresponding value of the directivity pattern function, then one has from equations (1) and (2)

$$(b^2)' = \frac{I'}{k} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

or $\qquad (20 \log b)' = EL' - K$

where $k = I_o \dfrac{\sigma}{4\pi} \cdot \dfrac{e^{-2\beta R}}{R^4}$

or $\qquad K = SL + TS - (40 \log R + 2\alpha R)$

The value of $(b^2)'$ or $(20 \log b)'$ is thus easily calculated for any target strength and range, and Ω' or θ' can be read directly from the curves of Figures 4.1A or 4.1D.

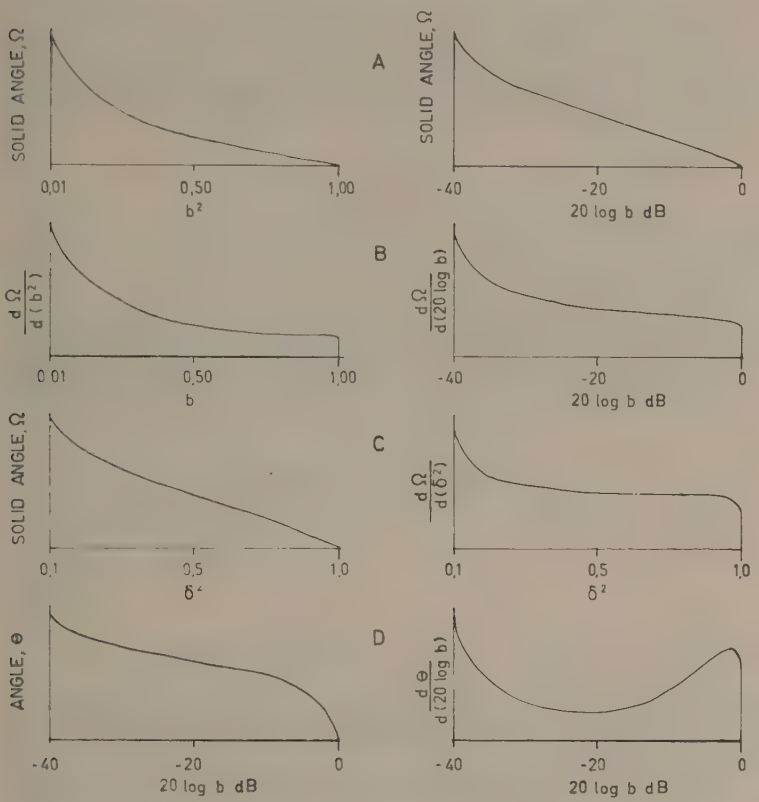


FIGURE 4.1 - Schematic presentation of relative number of echoes (proportional to Ω or θ) as a function of echo strength (proportional to b^2 or δ^2) when all fish have identical target strengths.

When the range slice of interest ΔR is no longer small compared with R, the total sampling volume becomes a more complicated function. If the limits of the range of interest are R_1 and R_2, then one must use the expressions

$$\text{sampling volume} = \int_{R_1}^{R_2} R^2 \, \Omega' \, dR \text{ per transmission} \quad \ldots\ldots(4)$$

or $$\text{sampling volume} = \int_{R_1}^{R_2} 2R\theta' \, dR \text{ per metre steamed}$$

for the two cases considered above. In general, Ω' and θ' will depend on R and will have to be calculated as a function of R before the integrals can be evaluated. However, when TVG is applied, as discussed in 4.2.1.4, Ω' and θ' become constant for a given target strength, so that the above expressions simplify to

$$\text{sampling volume} = (R_2^3 - R_1^3)\ \Omega'/3 \text{ per transmission} \quad \ldots\ldots\ldots(5)$$

or $$\text{sampling volume} = (R_2^2 - R_1^2)\ \theta' \text{ per metre steamed}$$

4.2.1.3 *Mean echo strength*

The mean echo intensity, like the sampling volume, can be measured in two basic ways. In the first case the mean of every received echo pulse is calculated, while in the second the mean of the maximum echoes from each fish is calculated. The mean for the first case is given by

$$\bar{I} = \frac{k}{\Omega'} \int_o^{\Omega'} b^2_{(\theta,\varphi)} \cdot d\Omega \quad \ldots\ldots\ldots\ldots\ldots(6)$$

and for the second by

$$\bar{I} = \frac{k}{\theta'} \int_o^{\theta'} b^2_{(\theta,\varphi)}\ d\theta \quad \ldots\ldots\ldots\ldots\ldots(7)$$

where k, Ω' and θ' are as defined in the previous section.

Since Ω' and θ' are known functions of k a plot of $\bar{I}$ against k can be readily made. Hence from measured values of $\bar{I}$, the corresponding values of k can be found, and since k depends on σ and R, the mean value of σ can be calculated.

Frequently, the echo amplitude is measured rather than the intensity, and the beam pattern coefficient $\delta_{(\theta,\varphi)}$ must be used instead of b. Similarly, the multiplier k must be replaced by a different factor a, where

$$a = \sqrt{\frac{I_o}{10^7\ \rho c} \cdot \frac{\sigma}{4\pi} \cdot \frac{e^{-2\beta R}}{R^4}} = \sqrt{\frac{k}{10^7\ \rho c}}$$

which gives the amplitude in microbars when multiplied by δ^2. The relevant equations for the two cases considered now become

$$\bar{p} = \frac{a}{\Omega'} \int_o^{\Omega'} \delta^2_{(\theta,\varphi)}\ d\Omega \quad \ldots\ldots\ldots\ldots\ldots(8)$$

and $$\bar{p} = \frac{a}{\theta'} \int_o^{\theta'} \delta^2_{(\theta)}\ d\theta \quad \ldots\ldots\ldots\ldots\ldots(9)$$

4.2.1.4 *Effect of time-varied-gain (TVG)*

Many difficulties arise in the application of the foregoing theory because of the loss of signal intensity with range of (40 log $R + 2\alpha R$) or

$$\frac{e^{-2\beta R}}{R^4}$$

since echo-strength distributions, sampling volume and mean echo strength all have to be calculated as functions of range. Some of the better echo sounders available incorporate TVG, whereby the receiver gain is changed with time at the correct rate to compensate for signal loss. The effect of TVG is to eliminate the signal intensity variations with range, and make measured echo strength depend only on $b_{(\theta,\varphi)}$ or $\delta_{(\theta,\varphi)}$, thus enormously simplifying the required calculations.

The most important effects of TVG are:

The effective sampling angle or solid angle becomes constant for a given target strength. As a result the sampling volume can be expressed simply by equation (5) irrespective of range.

The mean intensity from a population of given target strength becomes constant.

The relative echo-intensity distribution from a given population becomes constant with range.

When TVG is not available, some of its benefits can be attained if the fish of interest are found at a reasonably constant range. It is essential that the normal manual gain control of the sounder be calibrated, so that the gain can be set to the correct value for the range of interest.

4.2.1.5 *Measurements of target strength*

When a frequency distribution of echo strength is obtained, either by using an oscilloscope or an automatic device (pulse height analyser, computer) the distribution of target strength can be calculated provided that the directivity function of the transducer is known. The following analysis is described by Craig and Forbes (1969).

Since TVG is a full correction, the echo of any target is independent of range. The amplitude depends only on the angular coordinates of the targets.

The essential part of the treatment is to assume some density of fish, and deduce the echo distribution that would result. One then uses this to deduce density from echo distribution.

Consider any range slice lying between R_1 and R_2 in the beam, and let the solid angle be Ω. The volume in the range slice is

$$\int_{R_1}^{R_2} \Omega R^2 \, dR = 1/3 \; \Omega \; (R_2^3 - R_1^3) \quad \ldots\ldots\ldots\ldots (10)$$

Thus, if there are N_1 targets per cubic metre in this range slice ΔR, of target level — 40 dB, the number contained in the solid angle Ω is 1/3 N_1 Ω $(R_2^3 - R_1^3)$.

One now has to consider the directivity pattern of the equipment. This can be obtained theoretically by combining the transmit and receive directivities. Better, it can be obtained by direct field trial at some suitable range, for example 100 m. The complete way to show the results is to plot a cross-section of the beam and one may suppose this to have been done (Figure 4.2). The levels are arbitrary and have been chosen so as to include a suitable gain for the purpose. Since the beam angle is small, the area within a contour measured in (radian)^2 corresponds to the solid angle in steradians.

The —40 dB targets will be detected only in the centre area A_1, and the echoes will be between 0 and 1 dB. This is called channel 1. The number of echoes in this class is N_1 1/3 Ω $(R_2^3 - R_1^3)$ where it is now known $\Omega = A_1$.

Now consider there to be N_2 targets present of target level — 39 dB. These will give N_2 1/3 A_2 $(R_2^3 - R_1^3)$ echoes in channel 1 plus

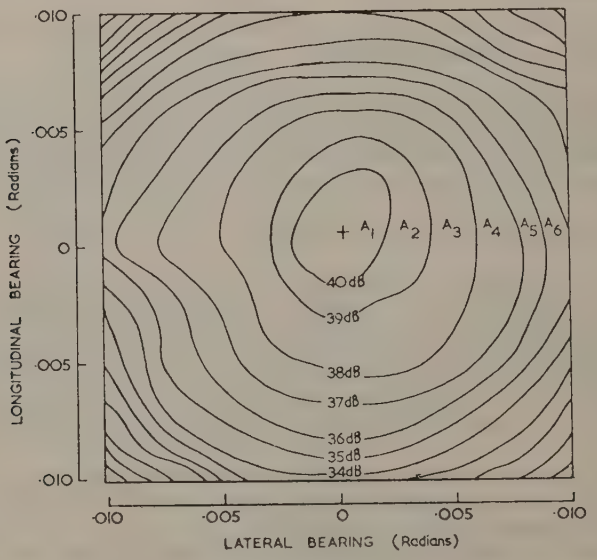


FIGURE 4.2 - Cross-section of acoustic beam pattern.

N_2 1/3 A_1 $(R_2^3 - R_1^3)$ echoes in channel 2 ...

and so on.

Suppose an eventual count in this depth slice was n_1 echoes in channel 1, n_2 in 2, n_3 in 3 and so on. Then one sees that

$$\left(\frac{3}{(R_2^3 - R_1^3)}\right) n_1 = A_1N_1 + A_2N_2 + A_3N_3 + \ldots\ldots + A_{20}\, N_{20} \quad \ldots.(11)$$

$$\left(\frac{3}{(R_2^3 - R_1^3)}\right) n_2 = A_1N_2 + A_2N_3 + \ldots\ldots\ldots\ldots + A_{19}\, N_{20}$$

$$\left(\frac{3}{(R_2^3 - R_1^3)}\right) n_3 = A_1N_3 + \ldots\ldots\ldots\ldots\ldots\ldots + A_{18}\, N_{20}, \text{ etc.}$$

giving 20 sets of equations.

A general solution can be found in the form

$$\left(\frac{R_2^3 - R_1^3}{3}\right) N_1 = B_1n_1 + B_2n_2 + B_3n_3 + \ldots\ldots\ldots + B_{20}\, n_{20} \quad \ldots.(12)$$

$$\left(\frac{R_2^3 - R_1^3}{3}\right) N_2 = B_1n_2 + B_2n_3 + \ldots\ldots\ldots\ldots + B_{19}\, n_{20}$$

$$\left(\frac{R_2^3 - R_1^3}{3}\right) N_3 = B_1n_3 + \ldots\ldots\ldots\ldots\ldots + B_{18}\, n_{20} \text{ etc.}$$

where the coefficients B_1, B_2 ... B_{20} are dependent only on the acoustic beam shape. A computer can put in the range corrections and print out the desired data in the form of target density as a function of target strength. If the observations are grouped in 3 or 5 dB groups, then the number of equations are reduced and the calculations can easily be done with a small slide rule.

When only the maximum echo from each fish is measured the solid angle Ω is replaced by the angle θ. The number of targets within θ is $N_1\, \theta.(R_2^2 - R_1^2)$ [see equation (5)]. The solution is

$$(R_2^2 - R_1^2)\, N_1 = C_1n_1 + C_2n_2 + C_3n_3 + \ldots\ldots + C_{20}\, n_{20} \quad \ldots\ldots\ldots.(13)$$

$$(R_2^2 - R_1^2)\, N_2 = C_1n_2 + C_2n_3 + \ldots\ldots\ldots\ldots + C_{19}\, n_{20}$$

$$(R_2^2 - R_1^2)\, N_3 = C_1n_3 + \ldots\ldots\ldots\ldots\ldots + C_{18}\, n_{20} \text{ etc.}$$

The above methods result in determination of the absolute density of fish by target-strength category, but require equipment to count and measure

every target. The relative number of targets of various sizes can easily be obtained by randomly counting and recording maximum echoes of fish passing through the acoustic beam. Since absolute density is not required and the range slice and distance steamed are constant for all categories, the equations reduce to the form:

$$n_1 = \theta_1 N_1 + \theta_2 N_2 + \ldots + \theta_{20} N_{20}$$

$$n_2 = \theta_1 N_2 + \theta_2 N_3 + \ldots + \theta_{19} N_{20}$$

$$\vdots$$

$$n_{20} = \theta_1 N_{20}$$

where: $N_1 \ldots N_{20}$ are the relative numbers of fish in each size category, and $\theta_1 \ldots \theta_{20}$ are the angles along the athwartship axis corresponding to the various dB levels of the directivity pattern function.

4.2.2 Multiple echoes and scattering layers

The intensity or amplitude distribution of echoes from single fish has been described in 4.2.1. In the case of multiple echoes, a different treatment is required, since the received echo level depends not only on the target strength and directivity, but also on the number of targets contributing to each echo, and to the phase of the received echo from each target. One must therefore consider some form of averaged signal instead of individual echo strength. It can be shown that, if several echoes of intensity I_1, I_2, etc. to I_n are received simultaneously, then, on the average, the combined total intensity is given by

$$I_T = I_1 + I_2 + \ldots + I_n \qquad \ldots\ldots(14)$$

and if the corresponding voltages received are V_1, $V_2 \ldots V_n$, then

$$V_T = \sqrt{(V_1^2 + V_2^2 + \ldots + V_n^2)} \qquad \ldots\ldots(15)$$

In the case of individual echoes of intensity I_1, $I_2 \ldots I_n$, one has the same relationship for I_T, but V_T is given by

$$V_T = V_1 + V_2 + \ldots + V_n \qquad \ldots\ldots(16)$$

Similarly, if one has n_1 echoes of intensity I in one multiple echo, and n_2 echoes of intensity I in a second multiple echo, then

$$I_{T_1} = n_1 I \qquad I_{T_2} = n_2 I$$

so that $I_T = I_{T_1} + I_{T_2} = (n_1 + n_2) I$ .....(17)

However, $V_{T_1} = \sqrt{n_1} V \qquad V_{T_2} = \sqrt{n_2} V$

so that $V_T = V_{T_1} + V_{T_2} = (\sqrt{n_1} + \sqrt{n_2}) V$ .....(18)

Clearly, then, it is better to measure multiple echo intensity rather than voltage if the measurements are to bear a simple relationship to fish population.

4.2.2.1 *Signal level*

Consider now a fish population as before of identical target strength and randomly distributed with a density of N per cubic metre, where the fish are now sufficiently close to give multiple echoes. The contribution of one fish can be written as

$$I = I_o \cdot \frac{\sigma}{4\pi} \cdot \frac{e^{-2\beta R}}{R^4} \, b^2_{(\theta,\varphi)} \quad \ldots\ldots\ldots\ldots (19)$$

Now the number of fish in the solid angle Ω is $NR^2.\Delta R\Omega$, and on average echoes are likely to come from any element of the beam solid angle. The depth slice from which echoes are received simultaneously is $\Delta R = c\tau/2$, so one can write for the instantaneous total received intensity

$$I_T = I_o \cdot \frac{\sigma}{4\pi} \cdot \frac{e^{-2\beta R}}{R^4} \int^{\Omega} NR^2 \, (c\tau/2) b^2_{(\theta,\varphi)} \, d\Omega \quad \ldots\ldots (20)$$

$$= I_o \cdot \frac{N\sigma}{4\pi} \cdot \frac{e^{-2\beta R}}{R^2} \cdot (c\tau/2) \int^{\Omega} b^2_{(\theta,\varphi)} \, d\Omega \quad \ldots\ldots\ldots (21)$$

Now $\int^{\Omega} b^2_{(\theta,\varphi)} \, d\Omega$ is a constant for a given transducer, and corresponds to the solid angle of an equivalent ideal beam, so one may write it as Ω_o

Therefore $$I_T = I_o \cdot \frac{\sigma N}{4\pi} \cdot \frac{e^{-2\beta R}}{R^2} \cdot \left(\frac{c\tau}{2}\right) \Omega_o \quad \ldots\ldots\ldots\ldots (22)$$

or in logarithmic terms:

$$EL = SL + TS + 10 \log N \left(\frac{c\tau}{2}\right) + 10 \log \Omega_o - (20 \log R + 2\alpha R) \ldots (23)$$

From equations (22) or (23), one can calculate

$$\frac{N\sigma}{4\pi} \text{ or } (TS + 10 \log N)$$

from the observed echo level and the parameters of the sounder, and, as will be shown later, this can give an estimate of the density of fish present in terms of weight per cubic metre.

In the case of scattering layers, the target strength or scattering cross-section of individual fish is no longer appropriate. However, one can introduce a volume-scattering coefficient s_v, where s_v is the ratio of the intensity scattered back toward the source by unit volume of the scattering layer to the intensity of the incident sound, both measured at 1 metre from the unit volume. One can replace $\frac{N\sigma}{4\pi}$ in the foregoing treatment by s_v, and hence obtain from equation (22)

$$I_T = I_o s_v \frac{e^{-2\beta R}}{R^2} \left(\frac{c\tau}{2}\right) \Omega_o \quad \ldots\ldots\ldots\ldots\ldots\ldots (24)$$

or if one puts $S_v = 10 \log s_v$,

$$EL = SL + S_v + 10 \log \left(\frac{c\tau}{2}\right) + 10 \log \Omega_o - (20 \log R + 2\alpha R) \ldots (25)$$

4.2.2.2 *Use of time-varied-gain*

In the multiple echo situation, the use of TVG can simplify the calculations as for the single echo case. The appropriate gain correction is now

$$\frac{e^{-2\beta R}}{R^2} \text{ or } \quad (20 \log R + 2\alpha R)$$

as can be seen from equations (22) or (23). If this value of TVG is used, then the integrated or averaged echo intensity becomes proportional to the fish population and no further correction for depth is required. This applies to all multiple echo cases where either intensity or voltage is used as a measure of fish density. When single fish echoes are encountered as well as multiple echoes, the situation becomes more difficult. If the average intensity of the signal is measured, then the mean intensity is given from equation (14) as

$$\bar{I} = \frac{1}{n} (I_1 + I_2 + \ldots + I_n) \quad \ldots\ldots\ldots\ldots\ldots (26)$$

However, for a given density of fish, the intensity of each echo will decrease as $R^4\ e^{2\beta R}$, while the number of echoes received will increase as R^2, so that

$$\bar{I}_R \text{ is proportional to } \frac{e^{-2\beta R}}{R^2} \quad \ldots\ldots\ldots\ldots (27)$$

Thus, in this case also, the appropriate TVG function is again (20 log $R + 2\alpha R$). If, however, the mean voltage is measured, the mean is given by equation (12) as

$$\bar{V} = \frac{1}{n}(V_1 + V_2 + \ldots + V_n) \quad \ldots\ldots\ldots\ldots (28)$$

Now the echo amplitude from a given size of fish decreases as $\sqrt{R^4\ e^{2\beta R}}$, or $R^2\ e^{\beta R}$ while again the number of echoes received will increase as R^2, so that

$$\bar{V}_R \text{ is proportional to } e^{-2\beta R} \quad \ldots\ldots\ldots\ldots (29)$$

This result shows that, if the average voltage received is taken as a measure of fish density, then for single fish targets no TVG apart from the attenuation correction is required. This difference between the single and multiple echo cases is one of the fundamental difficulties in using voltage averaging or integration. By squaring the voltage received before averaging or integrating, this problem can be overcome.

4.3 Practical methods

4.3.1 Presence and absence recording

The simplest form of echo counting is that based on the presence or absence of echoes from fish in any transmission.

Although the prime estimate is one of presence or absence within a transmission, the data can be treated quantitatively. In English investigations, the echo traces of pelagic fish are estimated in width (that is, in successive transmissions) at the widest point of the fish trace (Cushing, 1952). The records can be charted as millimetres of trace per 10 miles steamed. Here it is assumed that there are no changes in vertical extent of the trace, and that there are no significant variations in fish density and hence signal intensity.

If a form of grid survey has been used, areas of relative density can be

charted quantitatively. When such methods were combined with pilchard egg surveys, it was also possible to estimate the number of pilchards in an average trace (Cushing, 1957). Normally, however, the method will only indicate that one area is richer than another, relative richness being correctly given, if variations in fish density are random. However, no absolute quantity of fish is given with this technique unless catches between two areas have been correlated with quantities of echo trace.

4.3.2 Visual grading of echo recordings

The simple method of presence and absence is, however, rather inadequate when great variations in echo trace density (that is, degree of "blackening" of the paper) occur and/or the vertical extension of the individual traces vary much. This is frequently the case, especially with midwater sound scatterers, which are usually distributed in more or less continuous layers of varying densities during darkness, and from schools or aggregations of different stages in daytime.

The variations have to be taken into account and the simplest method is to establish a system of visual grading of the echo recordings. With trained observers this method can provide reasonably nonbiased estimates of echo abundance and has been used successfully, for example, to assess relative year-class strength of 0-group fish in the Barents Sea (Dragesund, 1970).

In the Barents Sea young fish surveys grades of echo density were used (Dragesund and Olsen, 1965) and this scale has subsequently been found useful for application in other waters where midwater scatterers are to be enumerated. A good example of such an application is that of the United Nations Development Programme (Special Fund) FAO Regional Fisheries Survey in west Africa, from which the classification description given below is derived.

Scattering layers

Type Try to distinguish between the following four types:

A. Smoke (plankton, etc.).

B. Recording consisting of small "grains" (very small single fishes).

C. Recording of small schools, less than quarter of a cable length in extension (not single fish traces).

D. Diffuse schools (the stage between typical layer and school).

Quantity 1. Very scattered — just colouring the paper (Figure 4.3A).

2. Scattered — between black and white (Figure 4.3B).

3. Dense — black (Figure 4.3C).

4. Very dense — black with some blocking (Figure 4.3D).

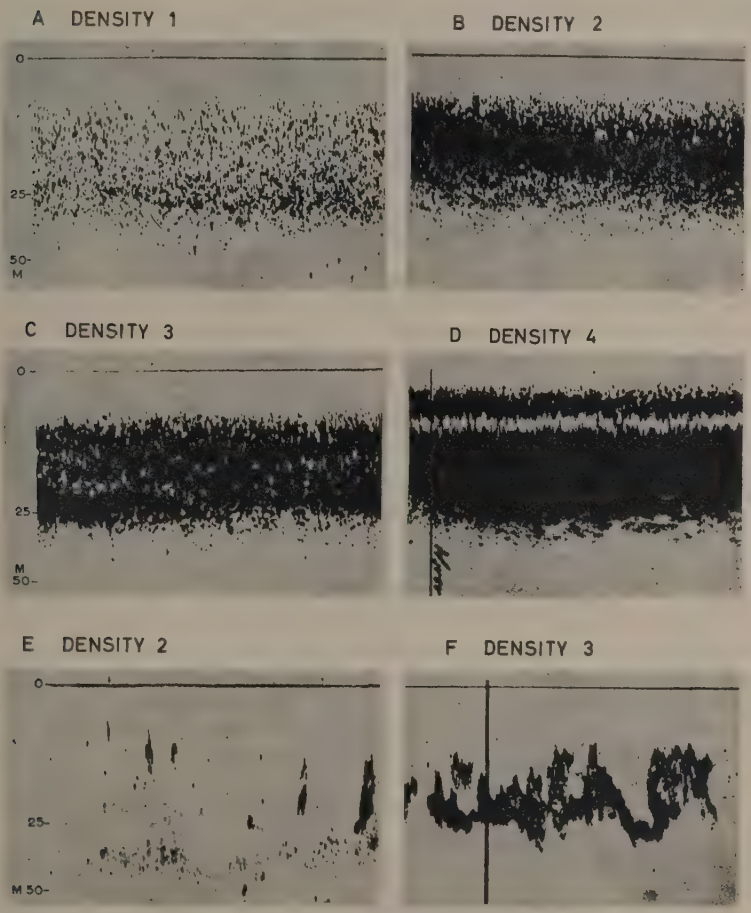


FIGURE 4.3 - Echo recordings of sound scatterers identified as 0-group herring, by night A to D and by day E and F. The densities of recordings E and F are comparable with those of B and C, respectively.

One serious disadvantage with this method is the unknown and non-uniform ratio between *true* fish densities corresponding to the ratios of echo classification. This has to be established empirically by sample fishing to permit summation of areas of different gradings of recorded echo abundance.

4.3.3 Counting and sizing of school recordings

Aggregations or schools of fish are usually easily located and recorded with an echo sounder or with a horizontal ranging sonar, and a simple count of number of schools per unit of distance steamed, or converted into number per unit of area, provides a first relative index of fish abundance of the area. Since fish schools may vary greatly in size such relative abundance estimates would be much improved if they were related to the volumes of the schools rather than to just the numbers. The estimation of school volume from echo sounder records alone, however, presents certain problems.

When a ship passes over a school of fish a conventional echo sounder will produce a trace describing a vertical cross-section of the school with height h and horizontal extension d. For estimating the volume of the school one might assume that it is of cylindrical shape and that the horizontal extension is the diameter of its base. This will in most cases underestimate the true volume of the school. However, if on the average the bias introduced is of the same relative magnitude for all school sizes of one species in a certain area, unbiased estimates of relative school sizes can be obtained if a large number of school measurements are being made.

In a successful echo survey, recordings of small schools may be very numerous and it would require a great deal of work to measure and record their exact dimensions from the traces and calculate individually their relative volumes. One way of overcoming this problem is to group the traces in a relatively small number of size categories and consider all schools in a category to equal the mean volume of that category. It is convenient to arrange the categories so that the ratio of volumes from one to the next one above remains constant, and for small schools experience suggests that the height of a school is increasing most often with its size at a relatively constant rate. Estimating the volumes as cylinders, one has:

$$V_1 = \pi \cdot h_1 \cdot r_1^2 , \qquad V_2 = \pi \cdot h_2 \cdot r_2^2 , \text{ etc.} \quad \ldots\ldots(30)$$

Defining $h_2 = f \cdot h_1$, and $V_2 = g \cdot V_1$, etc., one finds:

$$r_2 = r_1 \sqrt{g/f} \quad \ldots\ldots(31)$$

and similarly $r_3 = r_2 \sqrt{g/f}$, etc.

Consequently, the ratio between horizontal extensions of two consecutive categories will be constant and equal $\sqrt{g/f}$.

When measuring the horizontal extension of a school from its echo trace, allowance has to be made for the effect of the beam-width. Thus, if the longship beam angle is 20° the extension of a school at 25 m depth would be overestimated by approximately 8 m. This bias has to be subtracted from the trace length to find the true extension of the school cross-section. Note that the bias is independent of school size and, consequently, for larger schools its relative effect is small.

It has been found convenient to establish four size categories for grouping small schools covering the range of approximately one quarter to one cable length (one cable = one tenth nautical mile) in horizontal extension, and arrange their relative volumes so that they increase by a factor of four ($g = 4$) from one category to the next above. Most schools encountered will probably be within this size range and if it is assumed that the average bias in trace length is 8 m, and that the mean vertical extension increases from one category to the next by 50 percent ($f = 1.5$), being 8 m, say, for the smallest category, the mean dimensions will be those given in Table 4.1, below:

TABLE 4.1. — HORIZONTAL EXTENSION

School category	As measured from trace	Corrected for beam-width [1]	Vertical extension	Relative volume
A	50 m	42 m (0.23)	8 m	1
B	77 m	69 m (0.37)	12 m	4
C	121 m	113 m (0.61)	18 m	16
D	193 m	185 m (1.00)	27 m	64

[1] Figures in brackets are in cable length (one tenth nautical mile).

The correction for schools at 25 m range with a 20° fore-aft beam has been given as an example only. In Table 4.2 correction factors for the same beam angle are given by 10-m intervals from 10 to 120 m and, for a beam angle of 7°, in 20-m intervals from 20 to 240 m.

The corresponding trace lengths as measured in millimetres (with an echo sounder of paper speed 25 mm/min) are given in Table 4.3 for vessel speeds from 6 to 10 knots.

In practice it will not always be necessary to apply the above compensations since the difference in size between categories will, in general, be considerably in excess of such correction factors. However, in the case of deep schools, it is important to be aware of this problem.

It has been found very useful to make a drawing giving the external dimensions of the four standard categories in a series of outline diagrams

TABLE 4.2. — CORRECTION FACTORS

Fore-aft beam angle 20°		Fore-aft beam angle 7°	
Depth	Metres to be subtracted to obtain true extension of school	Depth	Metres to be subtracted to obtain true extension of school
Metres		*Metres*	
10	3	20	2
20	7	40	5
30	10	60	7
40	14	80	10
50	17	100	12
60	20	120	14
70	24	140	17
80	27	160	19
90	31	180	22
100	34	200	24
110	37	220	26
120	41	240	29

as they would appear for the normal cruising speed of one's own vessel. Such a reference chart can also be of great assistance in the grouping of small irregular schools.

When the vertical extension of a school differs by more than 50 percent from the standard height of that category, but has the same horizontal extension, it may be considered as a number of schools of that category; for example, in category A, two schools will be recorded for heights from 15 to 25 m.

TABLE 4.3. — CORRESPONDING TRACE LENGTHS

School category	Trace length for different vessel speeds				
	6 knots	7 knots	8 knots	9 knots	10 knots
	.....		*Millimetres*		.....
A	6.7	5.7	5.0	4.4	4.0
B	10.3	8.9	7.8	6.9	6.2
C	16.3	14.0	12.3	10.9	9.8
D	26.0	22.3	19.5	17.3	15.6

It was mentioned at the beginning that estimates of school size as outlined above are likely to be biased, and in the following this problem is studied in more detail. Consider again a cylindrical school of diameter d and height h, the volume of which is:

$$V_o = 1/4\ \pi\ d^2h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (32)$$

The probability of traversing such a cylindrical school (P_c) during an echo survey is independent of the direction from which the school is approached and is directly proportional to the diameter of the school:

$$P_c = pd \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (33)$$

where p is the unit probability (that is, the probability per length unit of the projection of the school's horizontal extension normal to the vessel's course).

The school will, however, only rarely be traversed exactly through ts centre, and the mean "diameter" estimated from the echo sounder recordings for a number of schools of the same size is given by

$$\bar{d} = \frac{\pi}{4}\ d$$

Thus, the volumes estimated from echo records of these schools are on an average underestimated by a factor of

$$\left(\frac{\pi}{4}\right)^{-2}$$

that is, by nearly 40 percent.

However, schools are not all of the same size and shape, and it could be assumed that as they grow in size they tend to deviate more frequently from the circular shape and become more elliptical, or even rectangular with rounded-off ends.

Now consider such an elliptical school, the volume of which is: $V_c = 1/4\ \pi hab$ when h is the height, and a and b the long and short diameters respectively. If the ratio between the two axes $a/b = k$ this becomes:

$$V_c = 1/4\pi hkb^2$$

The probability of hitting such a school is dependent on its angular orientation relative to the vessel's course; obviously the chance of hitting

it is greater when approached from the long side than from the short end, and:

$$P_e = p\ [b + (a\text{-}b)\ \cos\theta] \quad \ldots\ldots\ldots\ldots\ldots\ldots (34)$$
$$= pb\ [1 + (k\text{-}1)\ \cos\theta]$$

where θ is the angle of approach relative to the short axis of the ellipse.

The mean value of this is:

$$\overline{P}_e = pb\left[1 + (k\text{-}1)\cos\frac{\pi}{4}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (35)$$
$$= pb\left[1 + \frac{k\text{-}1}{\sqrt{2}}\right]$$

An equivalent circular school of the same height would have a diameter

$$d_e = \sqrt{ab} = b\sqrt{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots (36)$$

and the probability of hitting such a school:

$$P_c = pb\sqrt{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots (37)$$

As pointed out before P_c is independent of the angle of approach, that is, $P_c = \overline{P}_c$ and one has:

$$\frac{\overline{P}_e}{P_c} = \frac{pb\left(1 + \frac{k\text{-}1}{\sqrt{2}}\right)}{pb\sqrt{k}} = \frac{\sqrt{2}}{2}k^{\frac{1}{2}} + \left(1 - \frac{\sqrt{2}}{2}\right)k^{-\frac{1}{2}} \quad \ldots\ldots (38)$$

Since k is by definition >1, it can be shown that this ratio will also always be >1 and is increasing with k. In other words, the overall mean probability of hitting a school of a certain volume is smallest when the school is circular in horizontal extension, and for oblong schools it increases roughly proportionally to the square root of the ratio of the two axes.

It was seen previously that the volume of circular schools is on an average underestimated by a factor of $\left(\frac{\pi}{4}\right)^{-2}$ when estimated from echo recordings. For elliptical schools this bias is variable and may even become positive for schools with a high axis ratio. Thus for a certain axis ratio or school shape the bias is nil:

$$b\left[1 + (k\text{-}1)\ \sin\frac{\pi}{4}\right]\frac{\pi}{4} = b\sqrt{k_o} \quad \ldots\ldots\ldots\ldots (39)$$
$$k_o = 2.73$$

Consequently, if in fact small schools tend to be more circular than the bigger ones, and they become more elongated with size (that is, the axis ratio increases with school size), then volume estimates based on echo recordings from single crossings of the schools are systematically biased, underestimating the small schools and overestimating the big ones, with little or no bias at some intermediate school size.

It is evident that when schools are really large the error of estimating size from one routine crossing only could become very great, and when such big schools are located a special effort to establish true dimensions before the routine survey track is continued is strongly recommended. This can be done by crossing the school in several directions and/or by using a horizontal ranging sonar.

Such techniques are required if the true dimensions of each school must be determined. However, an unbiased measure of the relative abundance of fish in schools can be determined merely by measuring the relative proportions of transects occupied by schools. For example, if it is determined that after correction for beam-width 10 percent of the distance steamed along a transect was spent over schools of fish, then it may be assumed that, regardless of school shapes or individual sizes, 10 percent of the total survey area is occupied by similar schools. If school heights are variable, the relative volume occupied by schools can likewise be determined by summing the products of school heights times the transect proportions spent over schools.

A sonar alone can also be used for a complete quantitative survey to estimate the horizontal dimensions and abundance of fish schools in the upper layers of water, and a convenient method for such a sonar survey is described by Smith (1970). The sonar beam was kept permanently trained at 90° to the ship's course and records from targets within an intermediate-range interval were analysed. This range interval had been found from previous tests to be the most efficient one for that equipment and under prevailing sonar conditions in the sea.

The sonar records were used to estimate the number of schools and their horizontal extensions.

The apparent width of the fish school was calculated from the formula:

$$W_t = csl \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (40)$$

where W_t = the apparent width of the recorded fish school in metres
c = chart speed in seconds per millimetre
s = ship's speed in metres per second
l = measured width of target on chart in millimetres

The effect of the beam angle was corrected by subtraction of the width of the sonar beam at the midrange of the school:

$$W = W_t - 2 \tan \theta \left(\frac{R_{max} + R_{min}}{2} \right) \quad \ldots\ldots\ldots\ldots (41)$$

where W = the beam-corrected estimate of fish school width
θ = the half angle of the effective beam
R_{max} = range to the far side of the school in metres
R_{min} = range to the near side of the school in metres

The axis of the school normal to the ship's track was calculated by the formula:

$$d_i = R_{max} - R_{min} - 0.5\ p \quad \ldots\ldots\ldots\ldots\ldots\ldots (42)$$

where d_i = the axis normal to the ship in metres
and p = pulse length in metres (1 m.sec = 1.5 m)

During special trials the frequency distribution of the measured axis (d_i) normal to the ship did not differ significantly from the frequency distribution of the measured axis parallel to the ship for 37 targets ($X^2_{4d.f.} = 8.44$: not significant at the 95 percent level).

Schools were grouped in 250-m strips of range. Since this biases the size frequency distribution toward the smaller targets each count was corrected by the proportion of the width of the recorded strip which the target occupied. Thus, a 50-m diameter target could be recorded in its entirety on only 200 m of the record strip and would have been undersampled relative to 10-m diameter targets which could be recorded on 240 m of the strip. Correction for this "edge" effect is made in the following way:

$$N_i' = N_i \left(\frac{250}{250 - D_i} \right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (43)$$

N_i = the number of schools in size interval i
D_i = the diameter normal to ship's track representative of size interval i
N_i' = the number of schools in size interval i corrected for edge bias

To compare the size frequency distribution of the axes of the schooled targets at right angles to the ship (D_i) to the size frequency of the axes of the schooled targets parallel to the ship (D_j), the frequencies of N_i were corrected to the original number of schools whose D_i axes were less than 85 m. This correction is:

$$N_i'' = N_i' \left(\frac{\Sigma N_i}{\Sigma N'} \right) \quad \ldots\ldots\ldots\ldots\ldots\ldots (44)$$

where N_i and N_i' are as above and N_i'' is corrected proportionately so that the sum of N_i and the sum of N_i'' are approximately equal.

The area typical of the size class is calculated from:

$$a = \frac{(d_i)^2 \pi}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (45)$$

where a = the horizontal area of the schooled target
d_i = the midrange dimension of size class i in metres

However, the method described gives only an estimate of the horizontal extension of the schools in two dimensions, and apart from the general problem of identification the vertical extent of the schools has to be measured to estimate their volume, and some measure of density has to be applied to convert the volumes into numbers or weight of fish.

Soviet scientists have applied a method for estimating absolute abundance in this way and this has been particularly successful when used for large concentrations of fish in a restricted area, such as the overwintering aggregations of the mature stock of Atlanto-Scandian herring in a relatively small area between Iceland and the Faroes (Truskanov and Scherbino, 1966).

By means of a multiship survey a nearly synoptic distribution chart is made from which the volume of the total concentration is accurately estimated. This survey is carried out using both echo sounders and horizontal ranging sonars and the echo level in the different parts of the concentration is measured at the same time. The echo level distribution is thereby determined both vertically and horizontally (Figure 4.4), and if the relationship between echo level and fish density is known the absolute abundance of the fish concentration can be made.

This relationship was established experimentally in three ways:

An underwater camera was lowered into schools of different densities, and knowing the optics of the system and the size of fish in the schools the density could be estimated. Simultaneously the echo level of the schools was measured with a calibrated oscillograph.

At the same time a separate echo sounder transducer was placed amid the schools and, because of the short range, the recordings made resolved the schools into single fish traces from which density estimates were made.

The actual target strength of 25 to 30-cm herring was measured and experiments were subsequently conducted with artificial concentrations of models of equal target strength.

The results are shown in Figure 4.5.

These methods can be applied to many pelagic species and once the relationship between the incoming echo signal and the density of fish is

FIGURE 4.4 - Distribution of relative density within a herring school. (Scherbino and Truskanov, 1966.)

established, one can carry out an echometric survey and continuous measurements of echo level, from which density values can be plotted on a chart immediately.

The Soviet surveys were carried out with normal commercial echo sounders of 30-kHz frequency. Measurements of echo level were performed every 30 seconds, in the first years directly from a scope, but now this process has been somewhat automated by the use of a tape recorder.

4.3.4 COUNTING OF SINGLE FISH TRACES FROM THE ECHOGRAM

4.3.4.1 *Counting of traces alone*

The crudest method of dealing with single fish traces is simply to count the number of traces from the echogram paper, and use the number counted

per unit distance as an index of fish abundance. It is not possible in general to make absolute measurements of fish abundance by this method, unless the size distribution of the fish population is known in advance. However, useful relative measurements have been made in this way, particularly on cod in the Barents Sea.

The parameter of the sounder which determines the number of fish traces observed from a particular population is the sampling angle θ' described in 4.2.1.2. Clearly, the relative numbers counted from a given population density will increase with fish size as θ' increases, and Figure 4.1D shows the dependence of θ' on target strength in relative terms. Thus, the number of traces counted is a poor estimate of numerical fish density unless the size distribution remains constant. However, as the fish size increases, so does its weight, and if the count is used as an estimate of fish weight rather than fish numbers per unit volume a better estimate is obtained.

4.3.4.2 *Estimation of sampling volume from trace length*

A slightly more sophisticated approach to the counting of fish traces from an echogram uses the extra information available in the length of the

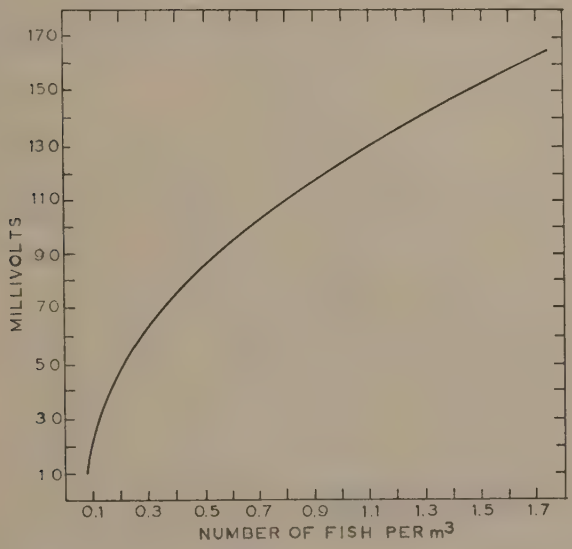


FIGURE 4.5 - Signal strength as a function of fish density. (Scherbino and Truskanov, 1966.)

individual traces. If the trace length on the paper is converted to the distance covered by the ship while the fish is detectable, a direct measurement of the mean sampling volume, and also the mean fish target strength, is possible if the directivity pattern of the acoustic beam and the calibration data of the sounder are known.

For any target strength, a fish will be detectable at a given range within an area $A = R^2\,\Omega'$, which is diagrammatically represented in Figure 4.1A. This area will cross the position of the fish, so that any fish will in effect pass along a chord of the area. Since the fish are equally likely to pass at any angle from the beam axis, the mean path length $\bar{l}$ of a fish within the beam is given by

$$\bar{l} = \frac{A}{d} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (46)$$

$$= \frac{R^2\,\Omega'}{2R\theta'}$$

where Ω' and θ' are as defined in 4.2.1.2.

For the simple case of a circular transducer, $\Omega' = \pi\theta'^2$, so that

$$\bar{l} = \frac{\pi R\theta'}{2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (47)$$

and

$$\theta' = \frac{2\bar{l}}{\pi R}$$

Thus the effective sampling area is $\frac{4\bar{l}\Delta R}{\pi}$. From the value of θ' obtained, it is possible to compute the mean target strength by applying the formulae of 4.2.1.2, if the sounder is calibrated.

For the more usual rectangular transducer, the shape of the beam area is rather more complicated. However, if one puts the ratio of the (athwartships) to (fore and aft) beam-widths equal to β, one obtains for an elliptical beam area

$$R\theta' = \frac{2}{\pi}\,\bar{l}\cdot\beta \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (48)$$

and for a rectangular beam area

$$R\theta' = \frac{1}{2}\,\bar{l}\cdot\beta$$

The shape of the beam from a rectangular transducer lies between these extremes, and it will be accurate enough for any purpose to put

$$R\theta' = \frac{1}{2}\left(\frac{2}{\pi} + \frac{1}{2}\right)\bar{l} \cdot \beta \quad \ldots\ldots\ldots\ldots\ldots (49)$$

$$= 0.56\ \bar{l} \cdot \beta$$

Thus the sampling volume per metre steamed is $1.12\,\bar{l}\,\beta\Delta R$.

4.3.4.3 *Counting combined with amplitude measurement*

Clearly, the more information obtainable from an echo sounder, the more accurate the results will be. By using a scope to measure echo amplitudes or intensities directly, considerable precision in determining sampling volumes and target strengths is possible. Perhaps the best-known work using this technique has been done by Cushing (1968), who uses a different mathematical treatment from that of 4.2.1.1. and 4.2.1.2.. The following description deals with the general case of a sounder without TVG.

An essential requirement for estimating abundance by this method is knowledge of the sampling volume of the echo sounder beam.

As shown in Section 1, the directivity coefficient, δ^2, decreases in angle θ from the axis to the first minimum, δ^2_{min}. Numbers of fish, however, increase as the square of the angle θ. Figure 4.6 shows the two distributions in angle θ. They can be multiplied to give a product distribution, the broken line in the figure. The mean of this product distribution in angle is the mean angle θ_m, which corresponds to the mean signal level.

The sampling volume of an echo sounder is described by the maximum range (R_{max}) of the target and the beam angle (θ). At a lesser range, R_1, the same signal is recorded as a minimum recordable signal at δ^2_{min} (corresponding with the angle θ_{min}). Therefore

$$R_1^{-2} = \frac{R^{-2}{}_{max}}{\delta^2{}_{min}} \quad \ldots\ldots\ldots\ldots\ldots (50)$$

Between R_1 and R_{max}, θ_m tends toward zero and δ^2_m tends toward unity. At intermediate ranges, taking ratios of R/R_{max} where R is any range intermediate between R_1 and R_{max}, intermediate values of θ_m, θ_{min}, δ^2_m, δ^2_{min} are calculable. Figure 4.7 shows the sampling volume of an echo sounder for fish of different sizes and hence of target strengths. At any range the sampling volume is given in m^3/m increment. It increases with range to an intermediate range after which it decreases sharply, as θ_m tends to zero. The area under each curve to a given maximum range represents the total volume sampled to that range.

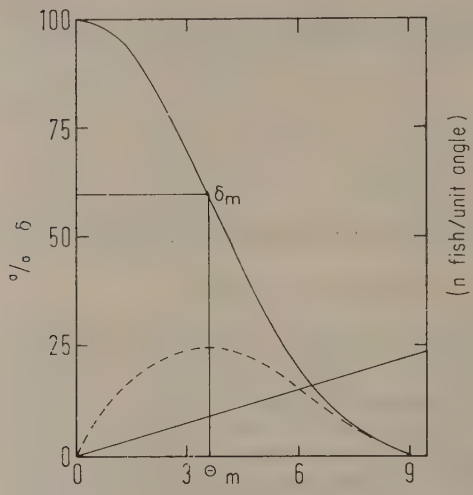


FIGURE 4.6 - Distribution of the directivity coefficient, δ, in θ, the angle from the axis of transmission (curved, full line); distribution of fish density in angle θ (straight line); the product distribution by multiplying fish density by δ in steps of θ (broken line).

The sampling volume can be split into slices, *range shell volumes.*

For a square transducer, the range shell volume between R_1 and R_2 and out to θ_{min} in angle is defined as

$$\frac{2}{3}\pi\,(R_2^3 - R_1^3)\;(1 - \cos\,\theta_{min}) \quad \ldots\ldots\ldots\ldots(51)$$

and, for a rectangular transducer, by

$$\frac{2}{3}\pi\,(R_2^3 - R_1^3)\;(1 - \cos\,\sqrt{\theta_\alpha\theta_\beta}) \quad \ldots\ldots\ldots\ldots(52)$$

where θ_α and θ_β are the angles subtended by the major ($R \sin \theta_{\alpha min}$) and minor ($R \sin \theta_{\beta min}$) axes of an ellipse at a range R.

The range shell volume is that in which a signal from a fish can be detected. It can be split into sectors of angle θ. Each sector is multiplied by the appropriate directivity coefficient and the sum of all sectors, so weighted, is the effective volume sampled; it takes into account the change of detection varying with directivity.

Any record of an individual target comprises a number of repeated signals in time. The numbers can be counted per unit time or distance. Thus for a vessel steaming for 30 minutes, at 9 knots, the number of effective volumes sampled is given by

$$\frac{n\,2R\sin\theta_{\beta min}}{9000} \qquad \ldots\ldots\ldots\ldots\ldots\ldots (53)$$

where n = number of fish, and R = the depth. So the number of individuals per 30 minutes steamed can be expressed as M/m^3. However, there is a bias due to the overlap of successive volumes. This bias can be considerable under certain circumstances and is described in an Appendix by J.C.K. Harris to Cushing (1968).

Numbers of fish are counted in unit distance steamed and could be expressed as numbers per total volume sampled in that distance, V_T. This volume is complex, its width being determined by θ_α, its length by the distance steamed and its height off the bottom on the axis by θ_β. There is also an error of the discontinuity of the repeated signals in time, a downward bias of 6 percent in 50 fathoms and 2 percent in 300 fathoms. The statistics of signals in a number of range shell volumes are fairly easy to handle while those for the total volume, V_T, are difficult.

The same system can be used to estimate the sizes of individual fishes in a statistical manner. Signal strength is calculated for any size of fish from

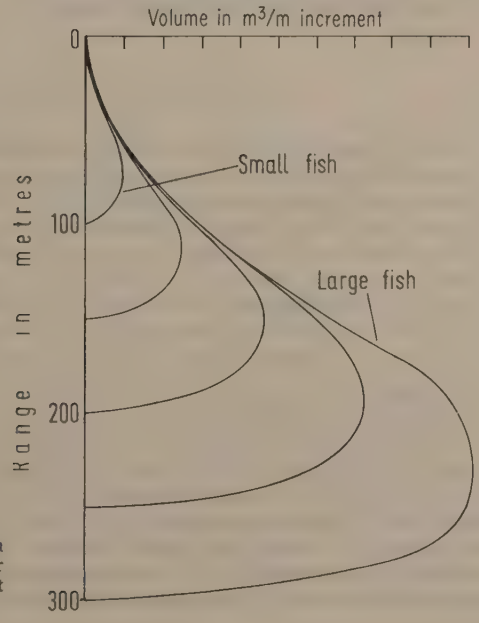


FIGURE 4.7 - Representation of the sampling volumes for fish of different sizes and target strengths.

$$V_{em} = \sqrt{k \frac{V_{sm}}{R^2}}\ \delta_m \quad \ldots\ldots\ldots\ldots\ldots\ldots (54)$$

where V_{em} = received voltage
V_{sm} = voltage of transmitted signal at source

At ranges greater than R_1, δ_m tends toward unity. So the signal strength is specified for any range as at an average position in the range shell. The points in Figure 4.8 are observed signal strengths (voltages) obtained on the continental shelf off South Africa and southwest Africa from readings taken with a Kelvin Hughes "Humber" echo sounder in February 1966.

Almost all the echoes were from individual fish and they lie in the range 20 to 90 cm. Indeed, the broken line shows the average signal strength by depth intervals, the bigger fish living in deeper water. The large circle at 210 fathoms represents the mean size of fish caught by trawl during the survey in three different areas; it will be seen that this size is very close to that estimated acoustically. In fact, the range of sizes sampled by trawl and by echo sounder were very similar, ranging from 20 to 90 cm. As much as 90 percent of the trawl catches were composed of hake; so it appears that most of the echoes were received from hake.

It is also possible to estimate the mean depth (or mean height above the bottom) using the mean angle, given by

$$R_2 = \left[R_1 - \frac{1}{2}(R_1 - R_2)\right] \cos\ \theta_m \quad \ldots\ldots\ldots\ldots (55)$$

Thus, given good conditions, it is possible to estimate numbers of individual fishes per cubic metre, their average sizes or their mean depths.

A similar technique has been used at the Marine Research Institute, Bergen, but the application is considerably simplified by the use of TVG and calibrated gain controls. The scope is calibrated in decibels and, by adjustment of the gain, the maximum signal level from any given target strength can be set to give a standard deflection on the scope. For example, the setting which gives a scope reading of +20 dB for the maximum echo from a —15 dB target strength might be chosen. The gain setting for the recorder can also be set, normally to give a minimum marking signal for zero dB scope deflection.

A survey is conducted by setting the gain controls appropriately to suit the expected fish population. During the survey, the signals received from single fish are observed and the maximum intensity in decibels is noted. As many fish echoes as possible are measured in this way, and the numbers of signals observed are noted in 5-dB intensity intervals. At the same time, fish traces are counted in depth slices of 25 or 50 m over distances of 1 nautical mile. Two methods are used for finding mean target strength and sampling volume. The first simply uses the mean signal

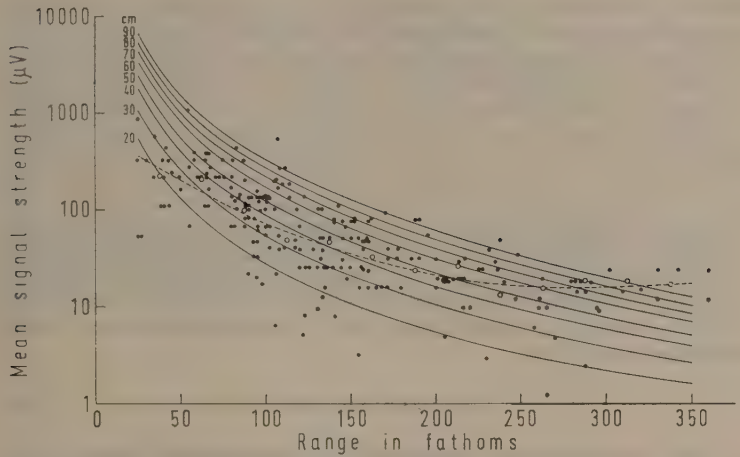


FIGURE 4.8 - Signal strengths (in μV) of fish between 20 and 90 cm as function of range (full lines) calculated from the sonar equation, as at $T.R^{-2}\,\theta m$. The points represent observed values of signal strengths in the four fathoms off the seabed. The broken line represents the trend of mean signal with range. The large black circle at 210 fathoms represents the size of fish (46 cm) in catches made by the commercial fleet during the echo survey.

strength calculated from the measured echo intensities to find the mean target strength and sampling volume from equation (7) of 4.2.1.3 and equation (5) of 4.2.1.2 respectively. The second method makes use of the distribution of echo numbers against intensity, and the expected distribution from a given size of fish, to find the actual distribution of target strengths.

4.3.5 SIGNAL AVERAGING AND INTEGRATION TECHNIQUES

4.3.5.1 *Signal averaging from a scope*

When fish are too closely spaced to be detected as individuals, some form of signal-averaging technique must be used. The visual grading of echo records discussed in 4.3.2 is one technique, but clearly better results can be obtained if actual voltage readings can be made from a scope. Considerable success has been obtained in this way by Truskanov and Scherbino (1966), and they have shown that the theoretical relationship that $V \propto \sqrt{N}$ where V is the observed voltage and N is the number of fish per cubic metre, is also true in practice. The technique requires that the voltage due to a school of fish or a scattering layer is read from the scope

for each transmission of the sounder, and is then squared and averaged, taking into account the loss of signal with depth of (20 log $R + 2\alpha R$) if no TVG is used. If possible the signals from different depths of the school or layer of fish should also be read, to give an indication of fish density variation with depth. The averaged readings are then converted to numbers of fish per cubic metre, and the densities found are plotted on a chart to show the spatial variation of density. Further details are given in 4.3.3.

This technique can give good results if most of the fish are of the same size. However, even if large variation in fish size is encountered, the averaged (Voltage)^2 can give a good indication of total fish density by weight rather than by number. It can be shown from equation (22), in 4.2.2.1, that if the signal loss with range is compensated for, either by calculation or by TVG, the received intensity is proportional to the product of number of fish per square metre, and the scattering cross-section of the individual fish, that is

$$I \text{ is proportional to } N\sigma \quad \ldots\ldots\ldots\ldots\ldots\ldots (56)$$

Now, the experimental measurements of target strength show that the scattering cross-section is very nearly proportional to the cube of the fish length for most sizes of fish of interest, or

$$\sigma \text{ is proportional to } l^3 \quad \ldots\ldots\ldots\ldots\ldots\ldots (57)$$

Therefore

$$I \text{ is proportional to } Nl^3$$

and since the weight of the fish is proportional to the cube of its length

$$I \text{ is proportional to } W$$

where W is the weight of fish per cubic metre.

Since I is proportional to V^2, one also has

$$V^2 \text{ is proportional to } W \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (58)$$

4.3.5.2 *Electronic integration*

The fundamental background for an electronic integration method for abundance estimation is given in 4.2.2, 4.2.2.1 and 4.2.2.2 and can be summed up as follows: when a TVG of 20 log $R + 2\alpha R$ is applied and the voltage is squared before it is integrated, then the output of an echo integrator bears a linear relationship to fish density both when single and multiple echoes are recorded. Equation (22) states that echo intensity, I, is proportional to fish density, N.

$$I = C\ N \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (59)$$

The output, M, of an echo integrator can be written

$$M = \sum_{0}^{P} \int_{\Delta R} I\ dR = \bar{I} \cdot \Delta R \cdot P \quad \ldots\ldots\ldots\ldots\ldots\ldots (60)$$

where $\bar{I}$ is the average echo intensity from a depth slice, ΔR, in a number of soundings, P. The number of soundings, P, is related to the echo sounder's pulse rate, p, the vessel speed, v, and sailed distance, l through

$$P = p \cdot \frac{l}{v} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (61)$$

and accordingly $$M = C \cdot \bar{N} \cdot \Delta R \cdot l \cdot \frac{p}{v} \quad \ldots\ldots\ldots\ldots\ldots\ldots (62)$$

This equation shows that the integrator output per unit distance and per unit depth is proportional to fish density when the ratio p/v is kept constant or is compensated for. A more convenient form of equation (62) for practical applications in echo surveying is

$$\frac{M}{l} \cdot \frac{v}{p} = C \cdot \bar{N} \cdot \Delta R \quad \ldots\ldots\ldots\ldots\ldots\ldots (63)$$

Now the left-hand side is proportional to number of fish per unit area surface, $N\ .\ \Delta R$, and this might be preferred when making charts of fish distribution. If the integrator itself automatically compensates for $\frac{v}{p}$ and recordings are obtained for equal distances (for instance, each nautical mile), then equation (63) is reduced to

$$M = C \cdot \bar{N} \cdot \Delta R \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (64)$$

Charts which show distributions of M are therefore showing relative numbers of fish per unit area surface.

So far it is assumed that C is a constant. As C depends on the scattering cross-section of fish and the characteristics of the instruments, the assumption is valid as long as the same equipment is used and the fish species do not change. Writing

$$C = C_I \cdot \frac{\sigma}{4\pi}$$

where C_I is an "instrumentation" constant, equation (64) can be written

$$\frac{M}{C_I} \cdot \frac{1}{\Delta R} = \frac{\sigma}{4\pi} \cdot \overline{N} \quad \ldots\ldots\ldots\ldots\ldots\ldots (65)$$

The right-hand side is now dependent on the scattering cross-section of the fish, σ, and fish density, $\overline{N}$. The left-hand side is exclusively observed and known (by instrument calibration) values, and thus the fish density $\overline{N}$ (or $\overline{N} \cdot \Delta R$) can be calculated when σ is known or observed. In logarithmic terms equation (65) is written

$$S_v = TS + 10 \log \overline{N} \quad \ldots\ldots\ldots\ldots\ldots\ldots (66)$$

or

$$S_A = TS + 10 \log (\overline{N} \cdot \Delta R) \quad \ldots\ldots\ldots\ldots\ldots\ldots (67)$$

where S_v is the volume back-scattering strength (4.2.2.1), S_A might be termed the area back-scattering strength and TS is the target strength.

When several species contribute to the recordings of M, one has

$$M = M_1 + M_2 + M_3 + M_4 + \ldots \quad \ldots\ldots\ldots\ldots (68)$$

where M_1, M_2, etc. are the contribution to M from the different species. This gives

$$M = \frac{C_I}{4\pi} (\sigma_1 \overline{N_1} + \sigma_2 \overline{N_2} + \sigma_3 \overline{N_3} + \ldots) \cdot \Delta R \quad \ldots\ldots\ldots\ldots (69)$$

Provided that frequent sampling (for instance trawling or purse seining) shows the true density ratios between species and that the scattering cross-sections are known, equation (69) makes it possible to estimate the densities of the different species.

The practical application of signal averaging or integration to obtain fish densities for stock assessments is limited by the difficulties involved in the discrimination between species when they are mixed. The question to be answered is: what are the different values of M_1, M_2, etc. in equation (68)? This can be estimated fairly accurately by experienced people who carefully examine the paper record of the echo sounder, the corresponding integrams, and the composition of the trawl catches. During an echo survey such inspections are quite necessary and should be carried out regularly, at least once a day, to ensure that mistakes like unfavourable

(or incorrect) settings, or failure of equipment, are discovered in time. When values of M_1, M_2 and so on are established, each of these can be considered as M in the equations (64) and (65).

In order to have distribution charts of M (relative abundance) replaced by N (or $N \cdot \Delta R$) (absolute abundance) there are different methods of approach:

When all the equipment is carefully calibrated so that C_l is known, then $\bar{N}$ (or $\bar{N} \cdot \Delta R$) can be found from equations (66) or (67), provided that the target strength of the fish is known.

When corresponding values of M and $\bar{N}$ (or $\bar{N} \cdot \Delta R$) are obtained, then C in equation (69) can be calculated and used as long as fish species and size distribution do not change.

There are, however, restrictions on the validity of equations (25), (66) and (67), as they are based on the following assumptions:

straight line propagation paths;

a random, homogeneous distribution of scatterers throughout the pulse resolution volume;

a density of scatterers so large that a number of scatterers occur in an elemental volume R^2 $(c\tau/2)$ $d\Omega$ (equation [20]);

no variation of target strength with aspect;

an absence of multiple scattering.

As these assumptions are only rarely met with in practice, estimates obtained using equations (66) and (67) will be biased. Due to the variation of target strength with fish aspect and the spatial orientation of fish the described technique may lead to underestimates.

Corresponding values of M and $\bar{N}$ can be obtained by counting fishes on a paper record when they are well resolved in single fish traces. The number of fish traces is next divided by the sampling volume (or area), thus giving $\bar{N}$ (or $\bar{N} \cdot \Delta R$).

Trials have also been made to obtain corresponding values of M and $\bar{N}$ from trawl or purse seine catches. Such experiments will be biased by the often unknown net avoidance of fishes. However, for scattered recordings of small fishes, using sufficiently large gear, trawling or purse seining might give fairly good estimates of fish density.

A method which has been used with success to establish the relation between signal amplitude and fish density is underwater photography (see 4.3.3).

Although there are difficulties to be overcome in making accurate estimates of fish density, automatic signal-averaging and integration

technique is far more accurate than the visual grading of the paper record. This is clearly demonstrated in Figure 4.9.

Detailed descriptions of instruments, their operation, maintenance and calibration are given in papers included in the reference list.

However, when an echo survey starts a setting-up procedure should be performed, and during the survey a control procedure should be followed. The most vital points of this procedure are listed below.

Choose the lowest echo strength value it is wished to record. Adjust the threshold and gain of the integrator and the recorder gain of the echo sounder so that this echo strength corresponds to the minimum recordable signal for both echo-sounder recorder and integrator.

Check that different integrator channels give equal readings at the same settings of threshold, gain and depth slice. Check that the ratios between readings obtained for equal signal inputs at different gain settings are correct.

Check that the bottom stop is on a suitable level (avoid bottom stop on fish schools).

Measure with an oscilloscope the signal input to the integrator and adjust the integrator gain to avoid saturation of the amplifier. (This point is of vital importance. If, for instance, the gain is used at 40 dB, but the signals received saturate the integrator at a gain of 20 dB, then the obtained values of M are at least 100 times too low.)

4.4 Survey and sampling considerations

The objective of acoustic assessment surveys is, generally, to obtain an estimate of the total number of fish within an area so as to either determine the relative number of fish from area to area or to study differences between years. Several methods have been presented to estimate fish density from analysis of echo signals. The volume of water searched by an echo sounder is usually a small proportion of the total volume of interest during a survey. Thus, the estimate of total abundance within an area is based on a number of samples within the area, and is subject to variability associated with fish distribution. In order to determine whether observed differences between areas or years are significant it is necessary to have some measure of the variability associated with the estimates. Further, optimal survey strategy must take into consideration both the distribution and the variability of fish density in allocation of survey effort.

A measure of the variability of fish density can be obtained from a number of observations within a given area. If a number of estimates of

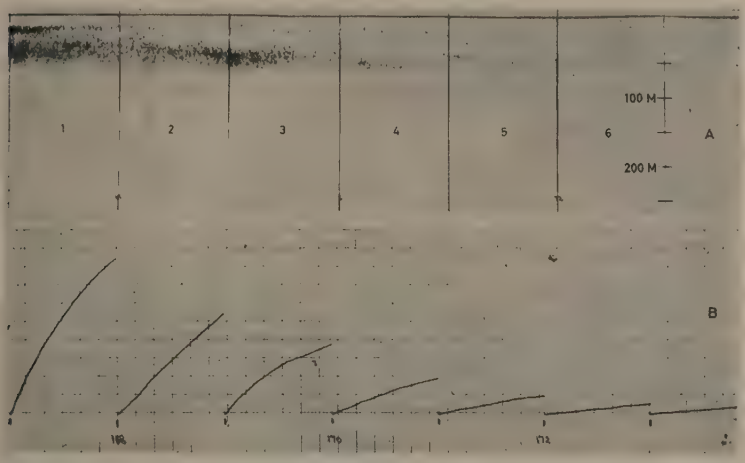


FIGURE 4.9 - Example demonstrating the use of the echo integrator. A: recording of sprat with echo sounder: 30 kHz, time-varied-gain. The distance between vertical lines represents one nautical mile. B: corresponding recordings on the echo integrator, depth range 6-60 m. (Bakken, 1970.)

fish density (I_i) are made, the mean value ($\bar{I}$) and its variance can be calculated from the formula:

$$\bar{I} = \frac{\sum_{i=1}^{n} I_i}{n}$$

$$\text{var } \bar{I} = \frac{S^2}{n}$$

where $$S^2 = \frac{\sum_{i=1}^{n} I_i^2 - \frac{(\Sigma I_i)^2}{n}}{n-1}$$ with $n-1$ degrees of freedom

The total number of fish in the area (N) is $\bar{I}V$ where V is the volume. Assuming the observations are normally distributed, confidence intervals for the estimate can then be calculated by the formula

$$C.I. = N \pm t_{.95.df}\, V \sqrt{\text{var } \bar{I}}$$

where $t_{.95,df}$ is the "t" value associated with 95 percent confidence intervals and $n-1$ degrees of freedom (df).

If several areas (j) of different densities are involved, the total number of fish can be obtained by summation

$$N_t = \sum_{j=1}^{m} V_j \cdot \bar{I}_j$$

The variance of the estimate of total fish abundance is

$$\text{Var } N_t = \sum_{j=1}^{m} V_j^2 \text{ Var } \bar{I}_j$$

and confidence intervals can be calculated as before

$$C.I. = N_t \pm t_{.95,df} \sqrt{\text{Var } N_t}$$

where

$$df = \sum_{j=1}^{m} (n_j - 1)$$

Normally during a survey there is insufficient time to make many replicate observations within a limited area. A practical way to obtain a measure of variance is to make a number of observations of fish density along preset tracklines and to group blocks of contiguous observations. This procedure assumes that each observation of density along the tracklines is an independent estimate of the density within the entire area associated with each block of observations. This procedure will often lead to an overestimate of the true variance.

An alternate method to grouping by area is to group observations by density strata according to the magnitude of the observation, as, for example, high, medium and low density strata. This procedure has the advantage of reducing variance by grouping similar observations.

The means and variances of each strata can be obtained as previously, where now the volume in each strata is the sum of the volumes associated with the individual observations within the strata.

SECTION 5. NEW DEVELOPMENTS IN SONAR TECHNIQUES

In the preceding sections attention has been confined to the description of the constructional and operational features of the two main types of sonar equipment – vertical echo sounders and echo-ranging sonars – currently in wide use for fish detection in commercial fishing and in research. In this section consideration is given to some of the new sonar techniques currently coming into use, at least in research, and which present important potential advantages over older equipment for many research purposes, and also, in some cases, commercial fishing. The techniques dealt with are electronic sector-scanning sonar, and continuous transmission frequency-modulated (CTFM) sonar.

5.1 Electronic sector-scanning sonar

5.1.1 Basic system

As described in Section 2, in an echo-ranging scanning system the receiving transducer is moved mechanically in azimuth to obtain the bearing of the target; however, scanning can be carried out electronically if the receiver is made up of a number of separate elements in the form of a linear array. The phase relationships of the echo reaching the separate elements of the receiver depend on the bearing of the target. When the target is on the acoustic axis in the far field, the signals received by the elements will all be in phase, and if the outputs are summed they will add in phase to a maximum; at all other bearings the signals received by the elements are out of phase and the summed outputs do not add up to a maximum. However, it is possible to compensate for the phase differences between individual elements by introducing local phase shifts, so bringing the summed output of the whole array to a maximum. If the phase relationships of the outputs are suitably modified, the direction of maximum sensitivity of the array can be steered in azimuth without moving the transducer.

Methods which might be used to steer the receiver beam are as follows:

by using a series of delay lines and a multiple switching device;

by sweeping the outputs of the receiver elements by a frequency-

modulated carrier and passing them into a tapped delay line where a phase shift is introduced as a linear function of frequency;

by suitable modulation of the outputs of the receiver elements.

Early developments in electronic sector-scanning sonar made use of multiple delay lines and real time delays, but such systems are relatively crude. The system developed by the Department of Electrical Engineering of the University of Birmingham, United Kingdom, uses a frequency-swept carrier and a single delay line, while the British Admiralty Research Laboratory Bifocal system uses multistage modulation scanning (Voglis and Cook, 1966).

Electronic scanning allows a wide sector to be covered very rapidly. For example, the British Admiralty Bifocal system has two modes of operation (the origin of the name Bifocal) which are analogous to the search and classified modes of CTFM sonar. In the wide sector mode the Bifocal scans a 30° sector at 10 000 scans a second, with a range resolution of 8 cm and a bearing resolution of 0.3°. In the close-up mode the scanned sector is reduced to 10° and the scanning rate increased to 30 000 scans a second, the range resolution being 2.5 cm. These scanning rates are so fast that the whole sector can be covered within the duration of the pulse of the returning echo. Within-pulse scanning means that the whole width of the sector is, for practical purposes, viewed simultaneously, so that no information is lost. The time taken to scan a sector therefore depends only on the range of maximum interest.

In both the Birmingham University and the Bifocal systems, range and bearing information are presented on a rectangular B. scan cathode-ray tube rather than a PPI display. While the PPI display gives a true plan picture (ignoring geometrical distortion) this is obtained at the expense of the lateral compression of information at short ranges, which must reduce some of the advantages of a high-bearing resolution. Some parameters of the Birmingham University and the Admiralty systems are given in Table 5.1.

5.1.2 Information given by sector-scanning sonar

The data summarized in Table 5.1 show that these electronic scanning systems have a very high range resolution and very narrow receiver beam-widths. It is interesting to consider how these parameters can affect the detail of the display and the ability to resolve, or separate, individual targets. For an example, consider the Bifocal equipment when used in the wide-angle mode. The 30° sector is scanned in the horizontal plane by a receiver with a beam-width of 0.33°. The range resolution is 8 cm, and the effective vertical beam-width of the scanned sector is 7.5°. The volume under surveillance is therefore divided into a large number of compartments and the picture shown on the display is a mosaic, but it

TABLE 5.1. — A COMPARISON BETWEEN THE PARAMETERS OF THE TWO ELECTRONIC SECTOR-SCANNING SYSTEMS

	Birmingham University system [1]	British Admiralty Bifocal system [2]
Type	Delay line	Modulation
Operating frequency kHz	500	300
Beam angle of horizontal sector insonified	30°	30° (s) [3] 10° (c) [4]
Horizontal sector scanned	30°	30° (s) 10° (c)
Receiver beam-width	1.0°	0.33°
Range resolution	10 cm	8.0 cm (s) 2.5 cm (c)

[1] Source: Welsby *et al.* (1963). — [2] Source: Voglis & Cook (1966). — [3] (s) = search or wide-angle mode. — [4] (c) = classify or close-up mode.

is important to note, as shown in Figure 5.1, that the horizontal and vertical dimensions of the compartments increase with range.

At 100 m, each compartment is 8 cm deep in range, 60 cm wide in azimuth and 13 m high in the vertical plane. At a range of 200 m the compartments are still 8 cm deep in range but are 120 cm wide and 26 m high. These compartments, which are slightly curved about the vertical axis, are the units of the mosaic of the cathode-ray tube display. The detail shown in the display is thus a function of compartment size and, therefore, range. If the reverberation of the sonar is limited, it is the volume reverberation (which could include surface or bottom reverberation) within these compartments against which the target echo must be detected. Two or more targets occupying the same compartment will be displayed as one target, and two targets of equal target strength occupying adjacent compartments cannot be resolved.

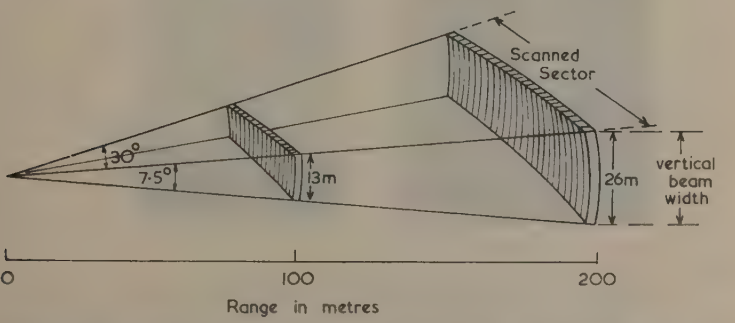


FIGURE 5.1 - Diagram to show increase in dimensions of compartment size, or scanning mosaic, with range. Scanning takes place in the horizontal plane over a 30° sector. The effective vertical beam-width is 7.5°.

5.1.3 Trials with sector-scanning sonar

Sector-scanning sonar equipment has now been used in a sufficient variety of field and laboratory trials, in connexion with problems of fisheries science, to demonstrate its potential value for a variety of problems (see Tucker, Welsby and Kendell, 1958; Tucker *et al.*, 1959; Harden Jones and McCartney, 1962; Welsby, Blaxter and Chapman, 1963; Welsby *et al.*, 1964; Tucker and Welsby, 1964; Voglis and Cook, 1966; Cushing and Harden Jones, 1966). The movements of individual fish have been studied in relation to acoustic stimuli, water flow in the vicinity of turbine intakes, warps, netting and a midwater trawl. The shape of some fish schools has been determined, and estimates made of the number of fish in them. The movements of schools have been followed in relation to each other and in relation to water currents. Observations have been made of a pelagic trawl and a bottom trawl, and there can be no doubts concerning the use of sector scanning for wreck detection and bottom survey work. Figures 5.2 and 5.3 show the sort of detail that can be obtained with this equipment in fisheries.

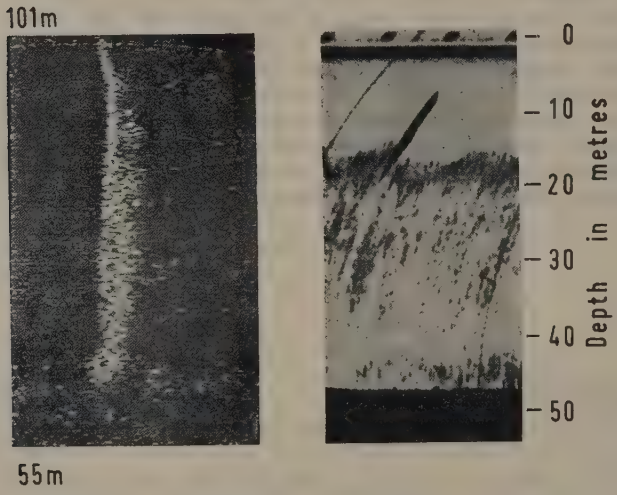


Figure 5.2 - A plume-shaped school recorded by vertical echo sounder and the Bifocal equipment. The sector scanner gives the plan projection of the school, which is long and narrow. The Bifocal display shows that the school is made up of separate units, which may be individual fish. The school is probably pilchards (Cushing and Harden Jones, 1966).

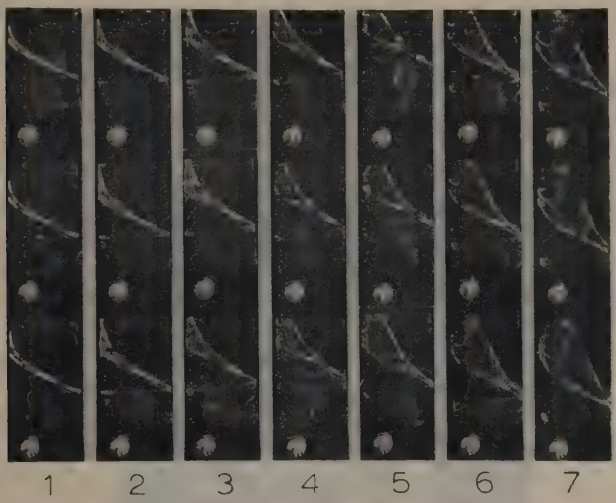


FIGURE 5.3 - A midwater Engel trawl as recorded on the display of the Bifocal equipment at a mean range of 100 m. The individual frames represent consecutive scans of the sector at a repetition rate of four per second, and should be read vertically in column 1, up to the top of column 2, down and up to the top of column 3, and so on. The vessel with the sector scanner is closing the range on the trawl. (Note that headline and foot-rope are displayed on the last frame of column 7.)

5.1.4 APPLICATION OF SECTOR-SCANNING SONAR IN FISHERIES WORK

The Voglis equipment — now known as the Admiralty Research Laboratory (ARL) sector scanner — has been operational on *R.V. Clione* since November 1969. Its performance has confirmed the potential value shown in earlier trials, particularly with regard to fish behaviour, gear, wreck detection, and bottom survey work. The shipboard installation (Mitson and Cook, 1971) allows the transducer to be turned so that scanning can occur in the vertical plane when the acoustic mosaic runs from surface to bottom rather than from left to right. A rapid switching between horizontal and vertical modes allows targets to be delimited horizontally and vertically, and the important practical consequence of vertical scanning is that it allows the depths to be determined accurately.

The ARL scanner is now being applied to a range of projects within the field of fishery science. Most effort has been directed toward the interaction between fish and gear, in particular the bottom trawl. The relatively wide-scanned sector allows the whole catching area of a standard Granton trawl to be kept under surveillance (Figure 5.4A), and one useful development is that the scanner can be used to identify "noisy" parts

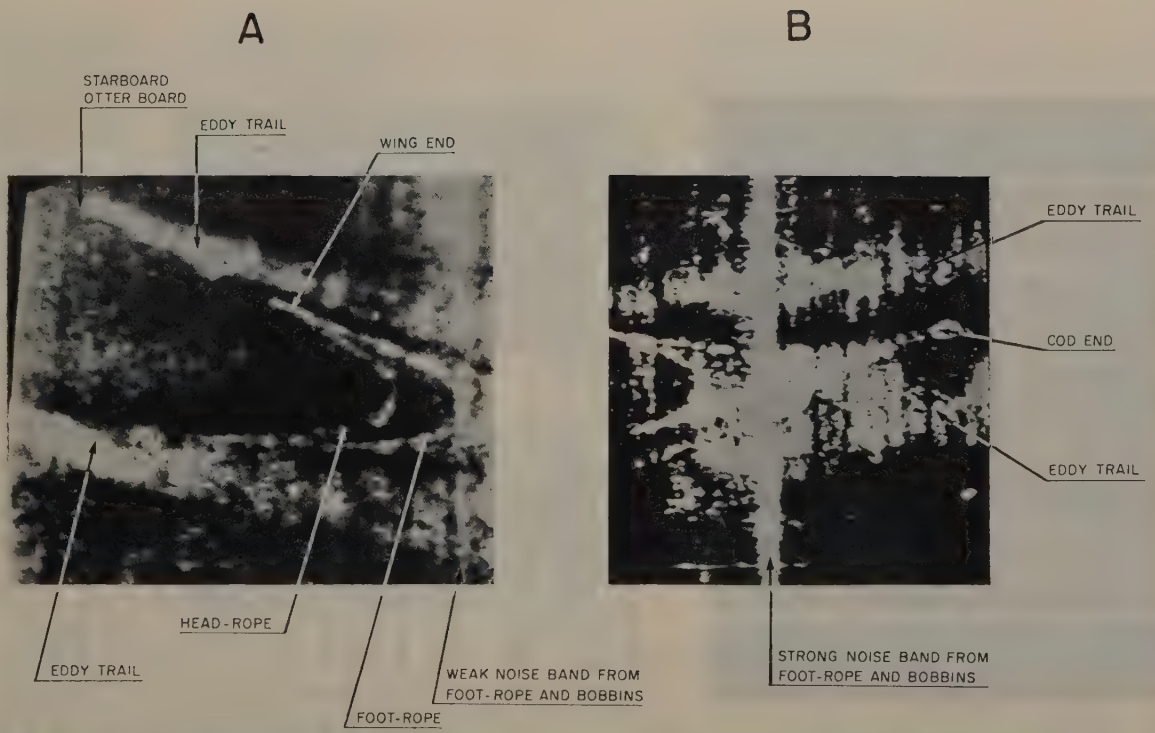


FIGURE 5.4 - A standard Granton trawl towed by *R.V. Ernest Holt* as recorded by the ARL sector scanner on *R.V. Clione*. Horizontal mode, mean range 100 m. Note that the whole mouth of the trawl is held under surveillance in A; in B a strong noise band is associated with the foot-rope and bobbins. Noise generated by different parts of the trawl varies with the type of bottom.

of the gear (Figure 5.4B) in a manner similar to that found for the seabed (Voglis and Cook, 1970).

Difficulties in identifying single fish against the seabed using the scanner in horizontal mode have led to the development of an acoustic transponding tag (Greer Walker, Mitson and Storeton-West, 1971). Plaice have been tracked from *R.V. Clione* for periods up to 52 hours in the open sea, and this new development provides the means to study the behaviour of single fish in relation to environmental factors and to examine the problem of vulnerability directly by releasing tagged fish in the path of a bottom trawl.

Horizontal and vertical scanning allows the shape and size of a fish school to be determined, and the high resolution of the equipment may allow direct estimates of the number of fish within the school. There are, of course, limitations to this technique in terms of fish-packing density and the size of the acoustic mosaic, which varies with range.

Other important applications include those of bottom surveys, a field receiving increasing attention in relation to the effects of gravel extraction on the seabed. Bottom topography, wrecks and pipe lines are other features for which the ARL scanner is a suitable survey instrument. With regard to underwater structures, the scanner has been used in studies on the blockage of water intakes by fish. Figure 5.5 shows sprat schools lying close to the intake of the nuclear power station at Dungeness, Kent, United Kingdom.

One problem which has so far received little attention is that of fitting a sector scanner into a ship. To be effective the limited sector must be trainable over a wide angle in azimuth, and with narrow receiver beamwidths stabilization must be provided against roll, pitch and yaw. If the equipment is to be used when the ship steams at a reasonable speed (say over 3 knots) some form of dome may be required to reduce the adverse effects of water noise over the face of the transducer, and to protect it from damage by driftwood and so on. If the dome has to be more than a streamline cover, it may have to be big enough to house the space envelope occupied by a mechanically stabilized transducer. It is clear that these requirements could raise important issues in ship construction and design, and thought should be given to these problems at an early stage when layouts could easily be designed to accommodate a scanner and its associated equipment at a later date.

5.2 Continuous transmission frequency-modulated (CTFM) sonar

5.2.1 Basic system

A type of sonar system that has recently found application in fishery work is the FM (frequency-modulated) or CTFM (continous transmission frequency-modulated) sonar. The basic system uses separate transducers

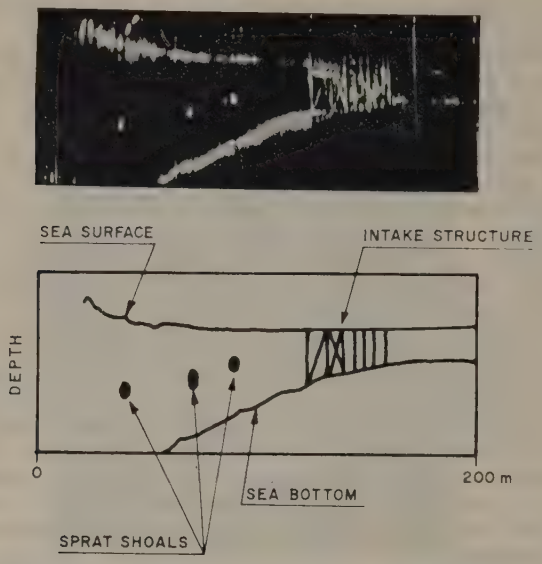


FIGURE 5.5 - Sprat schools lying close to the intake of the nuclear power station at Dungeness. Vertical mode, maximum range 200 m. Depth of water at intake about 10 m.

for transmission (projector) and echo reception (receiver hydrophone). The projector typically has a wide beam pattern — perhaps 25° horizontal by 20° vertical — and insonifies a large volume of water. The receiver hydrophone has a narrow beam pattern — perhaps 3° horizontal by 10° vertical — to provide good bearing resolution. The projector transmits continuously so that all the targets within its beam are insonified at all times. By scanning with the receiving hydrophone these targets can be detected immediately, without waiting (as is the case with a pulsed sonar) for the sound to make a round trip. In practice both projector and receiver hydrophones are scanned to cover a large sector. The scanning rate can be very rapid and is limited by the horizontal beam-width of the projector and the Doppler shifts across the faces of the hydrophones. In operational systems this is usually about 25° per second and the effect of Doppler shift can be minimized with the addition of the "oron Doppler nullifier."

The transmitted frequency is swept in a regular pattern (frequency modulation), typically sawtooth (Figure 5.6).

The frequency of the target echo (f_r) will differ from the transmitted frequency (f_t) by some difference frequency (Δf) that is proportional to target range. The transmitted frequency is swept over a range of a few

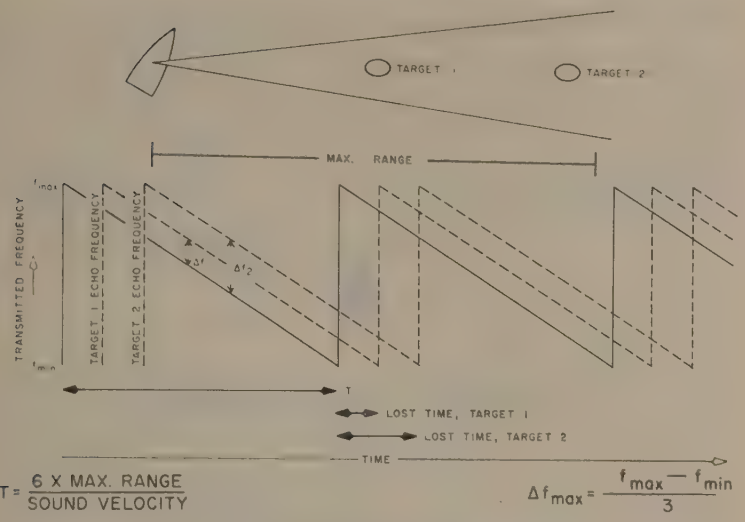


FIGURE 5.6 - Principles of CTFM sonar.

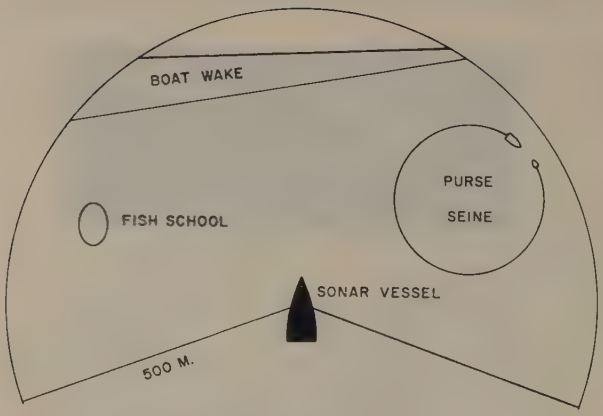
kHz. For example, a CTFM sonar might have a fundamental frequency of 50 kHz. The modulation range is usually designed to be three times the Δf band: if a Δf_{max} of 5 kHz is chosen then the transmitted frequency should be swept 15 kHz, or from 57.5 kHz down to 42.5 kHz. Targets at maximum range would be detected only during the last part of each sweep and the first portion of the sweep is "lost time." This is proportional to range; however, it can be eliminated with appropriate circuitry.

In the receiver electronics the difference frequencies (Δf's) are detected by a frequency analyser. Range resolution is limited by the number of filters — that is, by time constants and by the hydrophone scanning rate. This gives a range resolution of 1 m at 100 m or 16 m at 1 600 m maximum range.

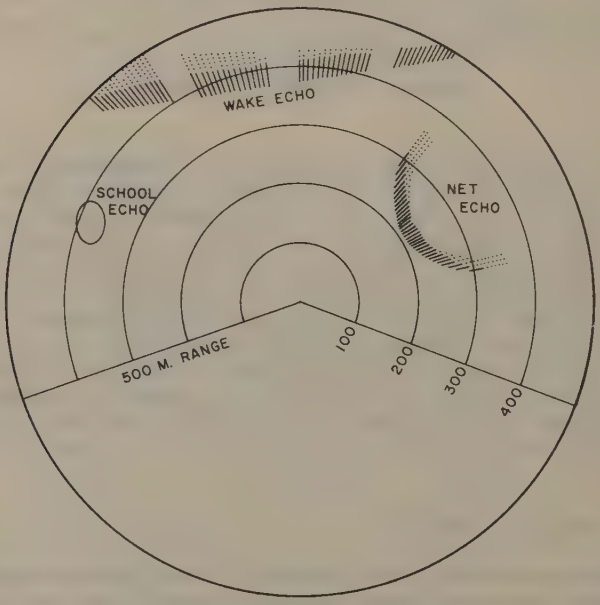
5.2.2 DISPLAY OF TARGETS

The output of the frequency analyser is changed to a video signal and presented as an intensity-modulated trace on a cathode-ray tube. Targets appear as bright spots displaced along the trace in increments of range on a PPI display, which is easily interpreted by anyone familiar with radar displays. This is shown diagrammatically in Figure 5.7.

Targets are also presented audibly. Since the Δf band lies in the audio



HYPOTHETICAL SONAR TARGETS



PPI DISPLAY OF ABOVE

FIGURE 5.7 - Diagrammatic representation of targets on CTFM sonar, PPI display.

range, further signal processing is unnecessary and target Δf can go directly to a loudspeaker or headset.

Fish and floating objects generally give a much clearer sound and video display than the bottom. Schools of small fish (sardine, anchovy) have a clear, bell-like echo against the falling tone of the transmission reverberations and make a bright spot on the CRT. Schools of large fish (tuna) generally have a scratchier echo and fuzzier video: the targets often disappear and reappear as the aspect of the school changes in relation to the beam. At close range (less than 100 m) large fish resolve into separate spots on the scope, whereas small fish do not.

5.2.3 Additional operational features of CTFM sonar

Sonar systems are designed as compromises between various factors of range, resolution, size and cost. CTFM systems can be designed to have long-range detection capability, excellent resolution, and small physical size — but such systems are extremely expensive. For fishery work cost is important and can be kept down by using minimal systems. If the cost is not of primary importance, however, a number of options can be included to increase the performance of the system. A basic CTFM system similar to the one described in the first part of this discussion can be built at a price competitive with an advanced pulsed sonar system.

5.2.4 Application of CTFM sonar

CTFM sonar systems are best suited for fishery problems that require rapid information flow, for example in the deployment of purse seines and the tracking of fast-swimming fishes. In these applications CTFM sonars have the following desirable features:

Rapid bearing scan and instantaneous range information.

Multiple target presentation on a PPI display. The persistence of the target trace on the cathode-ray tube simplifies maintenance of contact with the target and provides some indication of probable future target position.

Target echo fluctuation is minimized without loss of range resolution.

Since each target is a continuous secondary source its echo is present for the entire time it is in the receiving hydrophone beam path. During this time echo strength fluctuations associated with the path are averaged.

The major disadvantage of CTFM sonar for fishery application is its limited range, due to low transmitted power. Power output is limited primarily by the necessity to drive the projectors continuously, and secondly by cross-talk between projector and hydrophone.

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